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**THESIS**

**NUCLEAR AND SOLAR ENERGY: IMPLICATIONS FOR  
HOMELAND SECURITY**

by

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December 2008

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**NUCLEAR AND SOLAR ENERGY:  
IMPLICATIONS FOR HOMELAND SECURITY**

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## **ABSTRACT**

In the eyes of many experts, the world is moving away from oil as a cheap energy source. As this future unfolds, the United States may perform a leading role as the planet's premier energy consumer. Solar and nuclear power provide possibilities for this future which represent the extremes in terms of energy supply. The question this thesis asks is: what are the security implications of a substantial shift in energy policy in either a solar or nuclear direction? The analysis begins with a question, "What is a substantial shift?" and defines substantial in terms of energy shortage, energy independence, and climate change. The proposed energy futures to match these shifts are then judged with respect to three security criteria: resource access, nuclear weapons proliferation, and infrastructure protection. Accepting many uncertainties with future economic and technical solutions (even as proven systems are proposed), solar power provides the most stable future in terms of security alone. However, because these options are not mutually exclusive, both cases offer security challenges which are addressed in the concluding recommendations.

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## **LIST OF ACRONYMS AND ABBREVIATIONS**

CO2Eq	Carbon Dioxide Equivalent
CPI	Corruption Perceptions Index
CSP	Concentrated Solar Power
DBT	Design Basis Threat
DHS	Department of Homeland Security
EIA	Energy Information Administration
EROI	Energy Return On Investment
FBR	Fast Breeder Reactor
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HDI	Human Development Index
HHI	Herfindahl-Hirschman Index
HVDC	High-Voltage Direct Current
IPCC	Intergovernmental Panel on Climate change
NCEP	National Commission on Energy Policy
NRC	Nuclear Regulatory Commission
OPEC	Organization of the Petroleum Exporting Countries
Pu	Plutonium
PV	Photovoltaic
Quad	Quadrillion
U	Uranium

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## I. INTRODUCTION

### A. MAJOR RESEARCH QUESTION

Within the context of global warming, fossil fuel price increases, and national security concerns over energy recourses there exists a strong movement toward the adoption of alternative energy strategies. Two key alternatives that address this concern are nuclear and solar energy. These strategies are the chosen focal point for this thesis because they represent what might be called the boundary cases of the alternative energy spectrum. On one hand, nuclear energy represents a more mature technology, requiring traditional infrastructure, massive technical and bureaucratic capability, and access to a limited natural resource: uranium. Alternatively, solar energy embraces a variety of solutions from photovoltaic cells (PV) or wind energy to hydro-electric power or biomass fuels. Solar energy solutions will likely require a significant departure from traditional infrastructure systems. This gives rise to the research question at hand: what are the security implications for a substantial shift toward either solar or nuclear energy, and should one or the other be preferred for that reason?

### B. IMPORTANCE

The enormous consumption of energy by advanced industrial societies confronts their leaders with at least three significant challenges. First, assured access to energy, especially oil, at reasonable prices has become a national security priority, and a contributing factor to tension between nations. Second, fossil fuel consumption has been linked to environmental degradation and global warming according to the bulk of scientific analysis.<sup>1</sup> Global warming's climate change predictions include harmful effects ranging from food shortages and socio-economic instability to loss of endangered

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<sup>1</sup> R. K. Pachauri, Andy Reisinger and Intergovernmental Panel on Climate Change, "Climate Change 2007 Synthesis Report," IPCC.

species and shoreline property.<sup>2</sup> Thirdly, many predict that access to cheap fossil fuel energy is nearing a peak in production, after which such energy sources will become scarce, hence prohibitively expensive.<sup>3</sup>

Although solar and nuclear energy combined only account for a fraction of the energy provided by oil at present, each is proposed to replace oil dominance within the next 50 years or so. Because of energy's strategic value, any movement with regard to energy production has important security implications.

### C. PROBLEMS AND HYPOTHESES

To narrow down the many problems with nuclear and solar power to concerns with security questions alone, one can begin with questions surrounding either the resources required to support a system or the protection of the system itself. To evaluate an energy option, policy makers should favor choices which offer freedom from the security problems surrounding control over oil. Ideally, countries should not be able to hold each other hostage over energy resources. Because each energy option requires vastly different types of resources, one would expect different approaches to this problem. The resource security question for nuclear energy comes coupled with concern for nuclear weapons proliferation. A good strategy option will need to account for this security problem, a problem great enough to potentially outweigh other benefits. Finally, there is the problem for securing the energy systems themselves. Here both options offer very different solutions. Nuclear offers a central-plant-based power solution, which is easily matched to today's grid platform. Solar energy will likely involve a variety of power generation capabilities both large and small, which may also be distributed to end users in new ways. Protection of each of these systems will require different approaches. In the simplest terms, nuclear power will involve a few high-value targets, solar power

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<sup>2</sup> Siobhan Peters et al., *Stern Review: The Economics of Climate Change* (Cambridge CB2: Cambridge University Press, 2007).

<sup>3</sup> Robert L. Hirsch, *Peaking of World Oil Production: Recent Forecasts* (Washington D.C.: U.S. Department of Energy, National Energy Technology Laboratory, 2007).

will likely provide large numbers of small-value targets. The aim of this thesis is to consider which, on balance, represents the better overall choice from the point of view of national security.

#### D. LITERATURE REVIEW

Nuclear and solar energy constitute the major divisions in alternative energy options in the future. Not surprisingly, literature on both of these subjects is fraught with controversy. Furthermore, there is a lack of comprehensiveness to the discussion, as most articles only focus on a particular aspect of the debate. There is a tendency to show the strengths of one side and the weaknesses of the other. Critics of nuclear power claim nuclear power is too environmentally hazardous,<sup>4</sup> costs too much,<sup>5</sup> presents a security threat,<sup>6</sup> or will suffer the same fate as oil by virtue of being a non-renewable energy source.<sup>7</sup> Experts who favor nuclear power highlight nuclear power's low carbon emissions record,<sup>8</sup> economic feasibility,<sup>9</sup> and maintain that nuclear power can be more environmentally friendly than alternatives.<sup>10</sup> Solar power has drawn its share of critics as well. These experts claim that solar power is incapable of meeting demand efficiently,<sup>11</sup> involves toxic chemicals,<sup>12</sup> is the most expensive energy option,<sup>13</sup> and

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<sup>4</sup> Helen Caldicott, Nuclear Power is Not the Answer (New York: New Press: Distributed by W.W. Norton & Co, 2006), 39.

<sup>5</sup> Arjun Makhijani et al., "Carbon-Free and Nuclear-Free a Roadmap for U.S. Energy Policy," Takoma Park, MD: IEER Press; Muskegon, MI: RDR Books.

<sup>6</sup> David Bodansky, Nuclear Energy: Principles, Practices, and Prospects, 2nd ed. (New York: Springer, 2004), 512-513.

<sup>7</sup> David L. Goodstein, Out of Gas: The End of the Age of Oil, 1st ed. (New York: W.W. Norton, 2004), 106.

<sup>8</sup> John Deutch et al., The Future of Nuclear Power: An Interdisciplinary MIT Study (Boston, MA: Massachusetts Institute of Technology, 2003), ix.

<sup>9</sup> Steve Kidd, "Can we Ever Build Lots of New Nuclear Plants?" Nuclear Engineering International, March 31, 2004, 14.

<sup>10</sup> Gwyneth Cravens, Power to Save the World: The Truth about Nuclear Energy, 1st ed. (New York: Alfred A. Knopf, 2007), 193.

<sup>11</sup> Howard C. Hayden, The Solar Fraud: Why Solar Energy Won't Run the World, 2nd ed. (Pueblo West, CO: Vales Lake Pub, 2004), 98.

<sup>12</sup> Cravens, Power to Save the World: The Truth about Nuclear Energy, 249.

<sup>13</sup> Jerry Taylor, "Powering America: On the Road to Real Energy Solutions," *The RIPON Society* 3, no. 2 (June 12, 2007), 33.

will not develop fast enough to meet coming energy challenges.<sup>14</sup> Solar advocates counter with the fact that solar economics are becoming more favorable,<sup>15</sup> solar energy taps into an infinite resource,<sup>16</sup> solar solutions are cleaner than nuclear power,<sup>17</sup> and solar power allows an escape from grid infrastructure cost<sup>18</sup> and security problems.<sup>19</sup> Most authors recognize the inherent appeal of solar power; they only disagree about timing and the extent of its viability relative to anticipated demand.

With respect to security, expert analysis typically approaches the subject of nuclear and solar security from two angles. First, there is the question of the security of the resources that are required to produce the energy. Second, there is the question of the security of the infrastructure that makes up the energy systems themselves.

The national security concerns surrounding energy have been magnified by the prominence of oil, a cheap energy source that is generally consumed far from where it is produced. As nations perceive their stocks of cheap fuel dwindling, there has been a rise in the nationalization and militarization of energy reserves, a grave concern for the United States as a chief defender of a free energy market.<sup>20</sup> Writers such as Michael Klare have emphasized the ways in which disputes about oil might lead to international conflict.<sup>21</sup> Energy independence as a strategic goal for the U.S. has been a focal point

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<sup>14</sup> Michael T. Klare, *Rising Powers, Shrinking Planet: The New Geopolitics of Energy*, 1st ed. (New York: Metropolitan Books, 2008), 33.

<sup>15</sup> Peter Lorenz, Dickon Pinner and Thomas Seitz, "The Economics of Solar Power," *The McKinsey Quarterly* (July 9, 2008), 3; Travis Bradford, *Solar Revolution: The Economic Transformation of the Global Energy Industry* (Cambridge, MA: MIT Press, 2006), 132; Jennifer Kho, "Charting a Course to Low-Cost Solar," GreenTechMedia, <http://www.greentechmedia.com/articles/charting-a-path-to-low-cost-solar-1128.html> (accessed August 3, 2008).

<sup>16</sup> Bradford, *Solar Revolution: The Economic Transformation of the Global Energy Industry*, 5.

<sup>17</sup> Caldicott, *Nuclear Power is Not the Answer*, 171-172.

<sup>18</sup> Bradford, *Solar Revolution: The Economic Transformation of the Global Energy Industry*, 17.

<sup>19</sup> S. L. Klein, *Power to Change the World: Alternative Energy and the Rise of the Solar City*, 1st ed. (Charleston, SC: BookSurge Publishing, 2008), 372.

<sup>20</sup> Daniel Moran and James A. Russell, *Energy Security and Global Politics: The Militarization of Resource Management*, eds. Daniel Moran and James A. Russell (London; New York: Rutledge, 2009), 7-14.

<sup>21</sup> Klare, *Rising Powers, Shrinking Planet: The New Geopolitics of Energy*, 339.

since the 1973 oil crisis, and has been echoed in national policy statements since 9-11.<sup>22</sup> Calls to develop alternative energy as part of a national strategy can be found in several government documents.<sup>23</sup> Literature covering both solar and nuclear energy options touch on this possibility as well. A key question in this discussion: will the different energy options provide energy free from strategic struggles over resources? Klare makes the prediction that a struggle for uranium may well resemble the present day contests for oil.<sup>24</sup> The supply of nuclear material can be enhanced by reprocessing spent nuclear fuel in fast breeder reactors (FBR). These breeder reactors can take spent material and produce fissionable plutonium, which could increase the energy yield from a unit of uranium fifty to one hundred fold.<sup>25</sup> Unfortunately, the resulting supply of high-grade fissionable material presents additional risks because of its potential dual use in weapons programs.

The solar question is more difficult to predict, given the diversity of relevant technologies available.<sup>26</sup> From a security perspective, solar energy has particular appeal because access to the sun is universal. Solar energy is not likely to become a resource for which nations compete. However, a solar energy infrastructure may require resources that prove to be scarce, depending on the technology chosen. Production capacity for exotic elements such as germanium or gallium may need to be increased,<sup>27</sup> and nations with greater access may enjoy a superior position.

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<sup>22</sup> George W. Bush, "2006 State of the Union Address," White House, <http://www.whitehouse.gov/stateoftheunion/2006/> (accessed June 19, 2008).

<sup>23</sup> Thomas E. Morehouse Jr. "Climate, Energy, and Security—A Related Set of Challenges," In *Global Climate Change National Security Implications*, eds. Carolyn Pumphrey and others. (Carlisle Barracks, Pa: Strategic Studies Institute, U.S. Army War College, 2008), 281; CNA Corporation, *National Security and the Threat of Climate Change* (Alexandria, VA: CNA Corp, 2007); National Commission on Energy Policy, *Ending the Energy Stalemate. A Bipartisan Strategy to Meet America's Energy Challenges* (Washington DC: National Commission on Energy Policy, 2004).

<sup>24</sup> Klare, *Rising Powers, Shrinking Planet: The New Geopolitics of Energy*, 61.

<sup>25</sup> Von Hippel, Frank N., "Plutonium and Reprocessing of Spent Nuclear Fuel," *Science* 293, no. 5539 (Sep. 28, 2001), 2397.

<sup>26</sup> Mons Lonnroth , Thomas B. Johansson and Peter Steen, *Solar Versus Nuclear: Choosing Energy Futures* (Oxford: Pergamon P., 1980), 82-91; Bradford, *Solar Revolution: The Economic Transformation of the Global Energy Industry*, 238.

<sup>27</sup> Hayden, *The Solar Fraud: Why Solar Energy Won't Run the World*, 197.

Blended with the discussion of resource security is a challenge unique to the nuclear energy question, nuclear weapons proliferation. Concern over nuclear material and its use in developing a nuclear weapon has been a major policy issue in the United States.<sup>28</sup> Nuclear advocates are quick to point out that the eight original nuclear powers did not develop their nuclear capabilities through energy programs.<sup>29</sup> However, recent history in both India and Pakistan can serve to demonstrate than an energy program can be a useful avenue for developing a nuclear weapon program.<sup>30</sup> Although nuclear energy production can function without enrichment processes which can lead to nuclear weapons,<sup>31</sup> the steps to build a nuclear weapon capability from an energy program may be too tempting for nations to resist.<sup>32</sup> Breeder reactors could exacerbate the problem by multiplying the volume of weapons-grade nuclear material available. This security concern grows as national leaders consider the possibility of such materials falling into the hands of terrorists. Ideas to secure nuclear materials range from internationalization of enrichment activity<sup>33</sup> to the traditional security structures such as those the U.S. has built in Eastern Europe and Russia.<sup>34</sup> There is a need within the literature to portray the potential balance between the benefits of plentiful energy supply to national security against the costs for potential misbehavior with weapons proliferation.

The infrastructure security question involves examining the infrastructure with respect to each energy choice as a network of links and nodes required to function. Ted

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<sup>28</sup> The Whitehouse, *The National Security Strategy of the United States* (Washington D.C.: The Whitehouse, 2006); National Nuclear Security Administration, *Reducing Nuclear and Radiological Threats Worldwide* (Washington D.C.: National Nuclear Security Administration, 2007).

<sup>29</sup> Cravens, *Power to Save the World: The Truth about Nuclear Energy*, 152.

<sup>30</sup> William Langewiesche, *The Atomic Bazaar: Dispatches from the Underground World of Nuclear Trafficking*, 1st paperback ed. (New York: Farrar, Straus and Giroux, 2008), 70-103; Joseph Cirincione, Jon B. Wolfsthal and Miriam Rajkumar, *Deadly Arsenals: Nuclear, Biological, and Chemical Threats*, 2nd ed. (Washington, D.C: Carnegie Endowment for International Peace, 2005), 225,243-246.

<sup>31</sup> Cravens, *Power to Save the World: The Truth about Nuclear Energy*, 163.

<sup>32</sup> Langewiesche, *The Atomic Bazaar: Dispatches from the Underground World of Nuclear Trafficking*, 84-85.

<sup>33</sup> Cravens, *Power to Save the World: The Truth about Nuclear Energy*, 439.

<sup>34</sup> Matthew Bunn and others, "Securing the Bomb an Agenda for Action," Cambridge, MA: Harvard University: Nuclear Threat Initiative.

Lewis' textbook, *Critical Infrastructure Protection in Homeland Security*, provides a comprehensive review for the science of infrastructure network protection. He offers an analytical methodology for analyzing the network with regard to vulnerability and fault propagation. In other words, he examines how brittle the network is when things go wrong. Can one problem cascade into many? With respect to the solar versus nuclear power infrastructures, solar proponents like Travis Bradord, the President of the Prometheus Institute for Sustainable Development, indicate that the distributed power generation in solar power schemes will vastly reduce the centralized nature of the current grid system.<sup>35</sup> This will significantly alter the network analysis picture and change the risk equation for solar energy. This analysis raises the question of resilience in infrastructure design.

Resilience is a term that has recently emerged at the forefront of strategic thought with regard to infrastructure systems. C. S. Holling, an ecologist, is frequently cited to define resilience. He states:

Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist.<sup>36</sup>

Resilience in infrastructure is the “ability of a system to recover from adversity, either back to its original state or an adjusted state based on new requirements.”<sup>37</sup> Threats in the world of resilience advocates are not specific and not predictable, and since protection generally requires prediction, resilience offers a better approach. The question for alternative energy is which system provides greater resilience? Here solar advocates are most vocal. They are quick to point out that nuclear power involves the same rigid

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<sup>35</sup> Bradford, *Solar Revolution: The Economic Transformation of the Global Energy Industry*, 17.

<sup>36</sup> C. S. Holling, "Resilience and Stability of Ecological Systems," *Annual Review of Ecology and Systematics* 4 (1973), 17.

<sup>37</sup> John A. McCarthy, "Introduction: From Protection to Resilience: Injecting ‘Moxie’ into the Infrastructure Security Continuum," *CIP Program Discussion Paper Series; George Mason University* (2007), 2.

infrastructure systems as present day fossil fuel systems,<sup>38</sup> and that plant failures can be catastrophic.<sup>39</sup> Nuclear proponents emphasize the quality of their designs and resilience provided by better technology.

## E. METHODS AND SOURCES

Before evaluating each system with respect to security criteria, it is necessary to evaluate how much the energy market should change, and what these changes would look like for nuclear or solar power. For the purposes of this study, demand will be modeled after the United States, and energy solutions considered will be those technologies with some recorded performance. Sources will include literature as provided within the review augmented by government statistics or reports to explain resource locations and energy demand.

Criteria for this evaluation will engage both resource security and infrastructure protection questions, but will also consider broader questions of feasibility, as follows:

- **Resource access:** Will materials to support the energy options become national strategic resources to the degree that oil is today? Where are the resources? Who controls them? A system where resources are distributed abundantly throughout the international system would be preferable to a system where resources are concentrated within a few nations.
- **Nuclear weapons proliferation:** Although unique to the nuclear option, this is a key aspect to this analysis. No examination of nuclear energy can be complete without addressing this concern. Security solutions which minimize nuclear energy's facilitation of nuclear weapon development can be seen as more desirable if they reduce the concern to a level which would be present without nuclear power.

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<sup>38</sup> Bradford, *Solar Revolution: The Economic Transformation of the Global Energy Industry*, 82.

<sup>39</sup> Ibid., 72; Caldicott, *Nuclear Power is Not the Answer*, 64-68.

- **Network security:** How vulnerable are nuclear energy networks when compared to solar? This will apply many of Lewis' network security questions to each energy option. Resilience will be a sub-component of this discussion.

## F. THESIS OVERVIEW

On approach to the security criteria, the following chapters will first address the difficult questions about the scope of required changes, and how that change would be manifest for each alternative energy system. Each driver toward change, fossil fuel shortage, energy independence, and climate change, provides a different set of goals for change. Once these goals have been scoped, a following chapter will match an alternative energy future to each target. This way the security concerns as with regard to the thesis criteria are measured against an alternative energy movement tailored to a specific goal calling for the change. The criteria chapters will consider these inputs, while recognizing that a range of possibilities exist for each. As such, the criteria evaluations will provide a more qualitative measurement. The report will provide a chapter for each criterion followed by a summation of all evaluations. The conclusion will provide some security recommendations and suggestions for future research.

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## **II. SIZING THE REQUIREMENT**

Because the present research question examines a substantial shift in energy policy, it is worth considering what counts as “substantial” in this context. When judged as a driver toward alternative energy, the significance of any policy shift derives from its movement away from fossil fuels. So how far must the U.S. go in moving away from fossil fuels to make a difference? Each challenge, energy security, climate change, and oil scarcity, presents a different context to answer this question. The intent below is not to nail down an exact target, but to determine a general magnitude of change. Of particular interest will be the transportation sector, in which the substitution of non-fossil fuels for petroleum is universally recognized as especially difficult. Can a given policy produce significant change without requiring a major, enforced transformation of the transportation sector? The necessarily speculative (but almost certainly high) costs of such a transformation would have to be included in any calculation of the efficacy of the proposed policy.

As a point of departure, some explanation of the security challenges with the existing petroleum-based energy markets will help shape the consideration of alternatives. This study will use the U.S. Energy Information Administration (EIA) reference case within the Annual Energy Outlook 2008 to represent current policy direction.<sup>40</sup> Any alternative solution should not replicate the faults of the status quo. Good understanding of existing problems will enhance appreciation of nuclear or solar strategies and help refine criteria for evaluating options. The purpose of these requirements is to define the extent of change required, not to replace the security criterion. The bases of these requirements are broader than the security focus of this paper, but the latter cannot be realistically considered unless they are taken into account.

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<sup>40</sup> Energy Information Agency (EIA), "Annual Energy Outlook, 2008," U.S. Department of Energy, <http://www.eia.doe.gov/oiaf/aeo/index.html> (accessed September 15, 2008).

## A. OIL SCARCITY

As mentioned in the literature review, fossil fuels are finite resources, and as such any drawdown in supply which could affect the rate of production would substantially increase the value of remaining reserves. This shift in value could effect a considerable change in strategic power balance beyond what economic considerations alone would imply. Because the topic here is alternative energy, the question becomes when does oil scarcity necessitate alternative energy? As mentioned, there are a number of experts with a vast range of predictions. Even when examining a single source there is variability. Figure 1 provides the U.S. Geological Survey and the Energy Information Agency's future outlook with respect to this question.

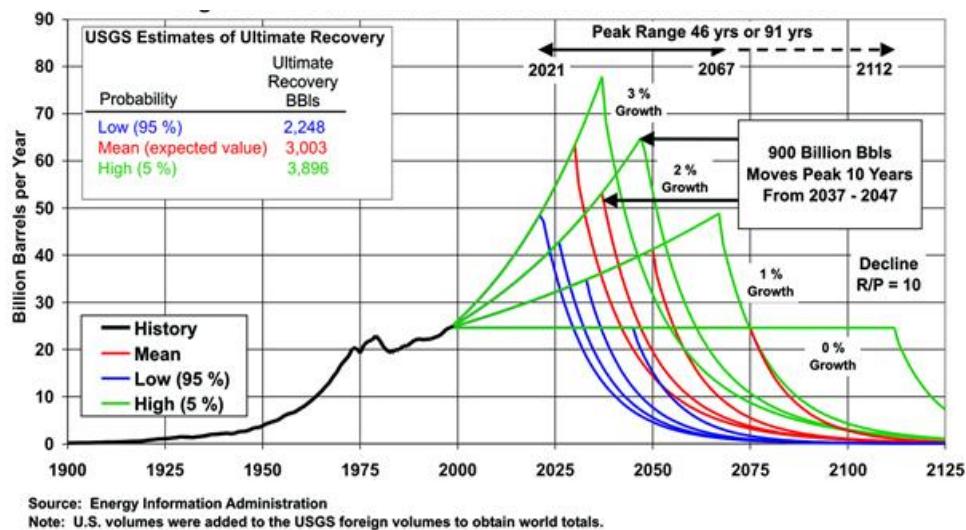


Figure 1. EIA Oil Production Scenarios<sup>41</sup>

EIA maintains that the predictions in Figure 1 are an update to Hubbert's original predictions using more reliable data.<sup>42</sup> The EIA reference case predicts a world

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<sup>41</sup> Energy Information Agency (EIA), "Long-Term World Oil Supply Scenarios," U.S. Department of Energy, [http://www.eia.doe.gov/pub/oil\\_gas/petroleum/feature\\_articles/2004/worldoilsupply/oilsupply04.html](http://www.eia.doe.gov/pub/oil_gas/petroleum/feature_articles/2004/worldoilsupply/oilsupply04.html) (accessed September 2008).

<sup>42</sup> Ibid.

production growth curve of less than two percent annually.<sup>43</sup> For this discussion, adopting a 2% growth rate may be a reasonable starting point. As such, oil production appears to reach a peak between 2025 and 2047. It is worth noting that the EIA reference case does predict some reductions in U.S. demand as a result of the Energy Independence and Security Act, but does not include the more wide-ranging measures considered in the following chapters.

Without getting into a highly speculative discussion, what does this problem suggest for alternative energy? It means that whatever changes are required, they should be well underway by 2030, the timeframe targeted for this effort. Because of the uncertainties in Figure 1 with respect to actual reserves, and because of the complex economic picture this graph represents, the oil scarcity question does not yield a clearly defined target beyond a rough timeframe for change.

## B. ENERGY SECURITY

The fourth essential task outlined in the U.S. National Security Strategy is to “ignite an era of economic growth through free markets and free trade.”<sup>44</sup> Enhancing energy security is part of this strategy with a goal to “open, integrate and diversify energy markets to ensure energy independence.”<sup>45</sup> The document goes on to suggest that an energy economy where a few countries control a majority of the resources is dangerous, and mentions the “oil curse,” a label for oil revenue and its role in encouraging corruption and resisting reform in economies singularly focused on oil.<sup>46</sup> Table 1 illustrates the current lack of diversity in the oil market today.

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<sup>43</sup> Energy Information Agency (EIA), "International Energy Outlook, 2008 Chapter 2 - Liquid Fuels," U.S. Department of Energy, [http://www.eia.doe.gov/oiaf/ieo/liquid\\_fuels.html](http://www.eia.doe.gov/oiaf/ieo/liquid_fuels.html) (accessed September 15, 2008).

<sup>44</sup> The Whitehouse, *The National Security Strategy of the United States* (Washington D.C.: The Whitehouse, 2006).

<sup>45</sup> Ibid.

<sup>46</sup> Ibid.

Table 1. Proven Oil Reserves and Oil Production – Top 15

Country	Oil Reserves <sup>47</sup>			2005 Crude Oil Energy Production <sup>48</sup>		
	Billion Barrels	Rank	%	Quad Btu	Rank	%
Saudi Arabia	262.30	1	20	20.60	1	13
Canada	179.21	2	14	5.02	11	3
Iran	136.27	3	10	8.89	4	6
Iraq	115.00	4	9	3.99	12	3
Kuwait	101.50	5	8	5.47	9	3
United Arab Emirates	97.80	6	7	5.36	10	3
Venezuela	80.01	7	6	5.74	7	4
Russia	60.00	8	5	19.41	2	12
Libya	41.46	9	3	3.44	13	2
Nigeria	36.22	10	3	5.64	8	4
Kazakhstan	30.00	11	2	2.77	14	2
United States	20.97	12	2	10.96	3	7
China	16.00	13	1	7.74	5	5
Qatar	15.21	14	1	1.76	15	1
Mexico	12.35	15	1	7.31	6	5
Rest of World	112.36		9	43.70		28
Total	1,316.66			157.80		

Three concerns should be addressed with the current energy scenario: cost to the U.S. economy, monopolistic control, and the nature of state control over oil. These concerns are sharpened by energy's foundational role in the U.S. economy and prominent national security interest.

## 1. Energy Independence

What degree of energy independence is necessary to avoid the economic damages which may result from continued dependence? State misbehavior in the oil business is of little concern if fossil fuels become a minor part of America's energy architecture. In

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<sup>47</sup> Oil and Gas Journal Figures from Energy Information Agency (EIA), Energy Information Agency (EIA), "World Energy Reserves," U.S. Department of Energy, <http://www.eia.doe.gov/iea/res.html> (accessed September 15, 2008).

<sup>48</sup> Energy Information Agency (EIA), "World Energy Production in British Thermal Units (Quadrillion Btu)," U.S. Department of Energy, <http://www.eia.doe.gov/iea/wepbtu.html> (accessed September 15, 2008).

2007, a team of experts writing for the Center for Transportation Analysis produced a report to answer this very question. Their report, *Oil Independence: Achievable National Goal or Empty Slogan?*, adds clarity to the energy independence discussion by providing a simple definition of oil independence. They suggest that energy independence is achieved when “costs of oil to the U.S. economy dependence is so small that they would have no effect on our economic, military, or foreign policy.”<sup>49</sup> Using risk analysis and the Oil Security Metrics Model, they determine that energy independence is achieved when the “estimated total economic costs of oil dependence will be less than 1% of the U.S. GDP with a 95% probability by 2030.”<sup>50</sup> Costs of dependence is expressed as transfer of wealth from consuming nations to producing nations as consumers pay a premium for access. Additionally, this cost will include loss of GDP from high oil prices as well as macroeconomic inefficiencies due to market volatility.<sup>51</sup> The study examines a National Commission on Energy Policy (NCEP) strategy which the authors estimate will reduce U.S. consumption by 7.22 Million Barrels/Day and increase U.S. domestic supply by 3.00 Million Barrels/day, causing a net decrease of 10.22 Barrels/day in imports as compared to the 2007 EIA reference case (early release energy outlook) by 2030. The modeled NCEP strategy achieves the 1% goal, but with only 68% probability, below the 95% probability goal. However, the reference case released later in 2008 already reflects demand reduction measures and has reductions comparable to the NCEP results within 2 Million Barrels/day. To approximate an energy independence target, this effort will set a 5-Million Barrel/day reduction goal for energy security. This would equate to 10.6 Quadrillion (Quad) Btu/yr.

Does this require a change in the transportation sector? If the 5 Million Barrels/day reduction is projected against the EIA reference case as shown in Figure 2, the oil supply minus the reduced import supply approaches the 2030 transportation sector demand. Therefore, change is not urgent by 2030, but will not be long after.

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<sup>49</sup> David L. Greene and et al., *Oil Independence: Achievable National Goal Or Empty Slogan?* (Oak Ridge, TN: Oak Ridge National Laboratory 2007).

<sup>50</sup> Ibid.

<sup>51</sup> Ibid.

## Oil Demand with Import Reductions

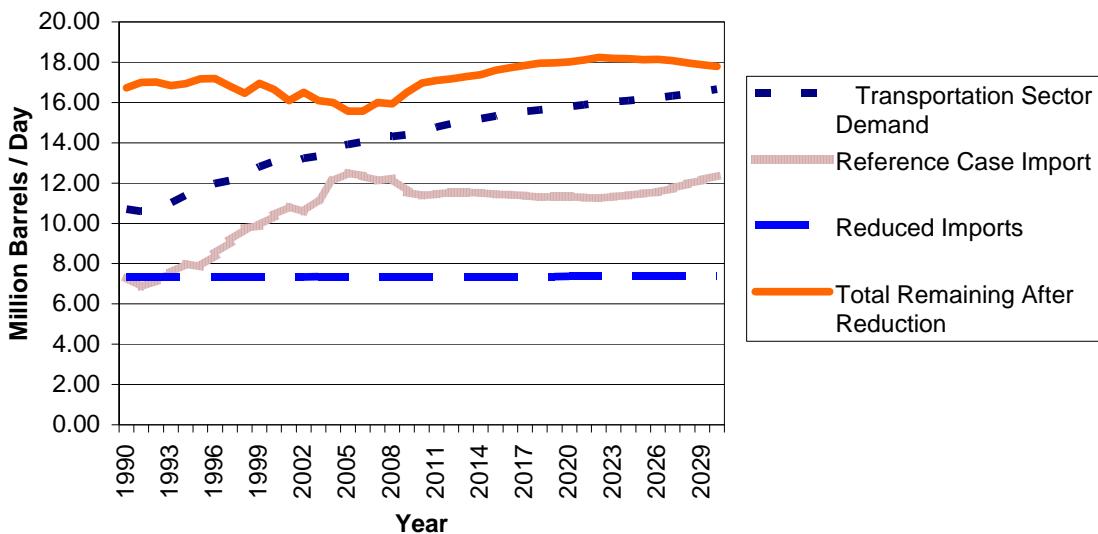


Figure 2. EIA Oil Production Scenarios<sup>52</sup> With severe cuts in imports, the United States would have just enough oil remaining in 2030 to support transportation fuel demand from the EIA reference case.

## 2. Market Distribution

The preceding economic discussion, yields a target for energy reduction, but does not completely address a key flaw in the fossil energy market in ways that can be used to compare with other energy options. Consider the scenario where countries hostile to the United States can exert monopolistic control over the energy market. If they decide to use the “oil weapon” as key members of the Organization of the Petroleum Exporting Countries (OPEC) did in the 1973 oil crisis, they can drive up prices to harm the U.S. economy. Strategic interests may trump market forces causing conflict, economic chaos, or even market collapse. Although complex models have been developed to examine oil

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<sup>52</sup> Energy Information Agency (EIA), "Oil and Natural Gas Projections," U.S. Department of Energy, <http://www.eia.doe.gov/oiaf/aeo/gas.html> (accessed September 15, 2008).

energy security,<sup>53</sup> this endeavor will boil the question down to a simple principle: energy markets vulnerable to cartel or monopolistic control are detrimental to U.S. security interests. Although there have been times where price controls have been necessary to counter the volatility in the oil market.<sup>54</sup> Promoting stability is the stated purpose of OPEC.<sup>55</sup> However, monopolistic control provides the power for states to manipulate the U.S. economy, a grave security concern when considering potential hostilities between the U.S. and oil producing nations. This is a key driver behind the energy independence target, and any new strategy should provide a measurable improvement in market conditions. No single metric can capture the complexity of the energy market, but there are measures of market vulnerability to monopolistic control which may add to the discussion.

Rather than concluding with an impression based on Table 1, one could utilize a more objective index to illustrate market conditions for comparison. The U.S. Department of Justice (DoJ) uses the Herfindahl-Hirschman Index (HHI) to gauge market concentration as an indicator for potential anti-trust concerns with mergers.<sup>56</sup> The index, as DoJ computes it, is simply the sum of the squares of the market share percentages in a given market. An HHI rating of under 1,000 indicates a freely competitive market. A score of 1,000 to 1,800 reflects markets which are moderately consolidated. HHIs above 1,800 represent markets which are considered consolidated, and warrant the attention of the DoJ if future mergers change this rating by over 100. However, the unique properties of the oil industry challenge any normal concept of market share. In some cases the competitors are companies, and in some cases they are states (most known oil reserves

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<sup>53</sup> A detailed model to examine energy options with respect to oil security, here used to examine the benefits of hybrid vehicle technology. David L. Greene and Paul N. Leiby, *The Oil Security Metrics Model: A Tool for Evaluating the Prospective Oil Security Benefits of DOE's Energy Efficiency and Renewable Energy R&D Programs* (Oak Ridge, TN: Oak Ridge National Laboratory,2006), [http://cta.ornl.gov/cta/Publications/Reports/ORNL\\_TM\\_2006\\_505.pdf](http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2006_505.pdf) (accessed September 15, 2008).

<sup>54</sup> Leonardo Maugeri, *The Age of Oil: The Mythology, History, and Future of the World's most Controversial Resource* (Guilford, Conn: Lyons Press, 2007), 45-46.

<sup>55</sup> Organization of the Petroleum Exporting Countries (OPEC), "How does OPEC Function?" Organization of the Petroleum Exporting Countries, <http://www.opec.org/library/FAQs/aboutOPEC/q4.htm> (accessed September 15, 2008).

<sup>56</sup> U.S. Department of Justice, "The Herfindahl-Hirschman Index," U.S. Department of Justice, <http://www.usdoj.gov/atr/public/testimony/hhi.htm> (accessed September 15, 2008).

are currently controlled by national oil companies). Reserves are also known to be limited, and production market share does not match reserve inventory. On one hand, annual production figures may seem appropriate for market share measurement, as one would expect in most cases as far as production might match sales. Yet, there is the question of oil reserves. Because demand is almost guaranteed, reserves are more important than marketing. Countries with significant oil reserves have additional clout in setting policies and prices, beyond what their annual production numbers would indicate. Rather than becoming entangled in the specifics, Figure 3 provides HHI considering both reserves and production perspectives for discussion.

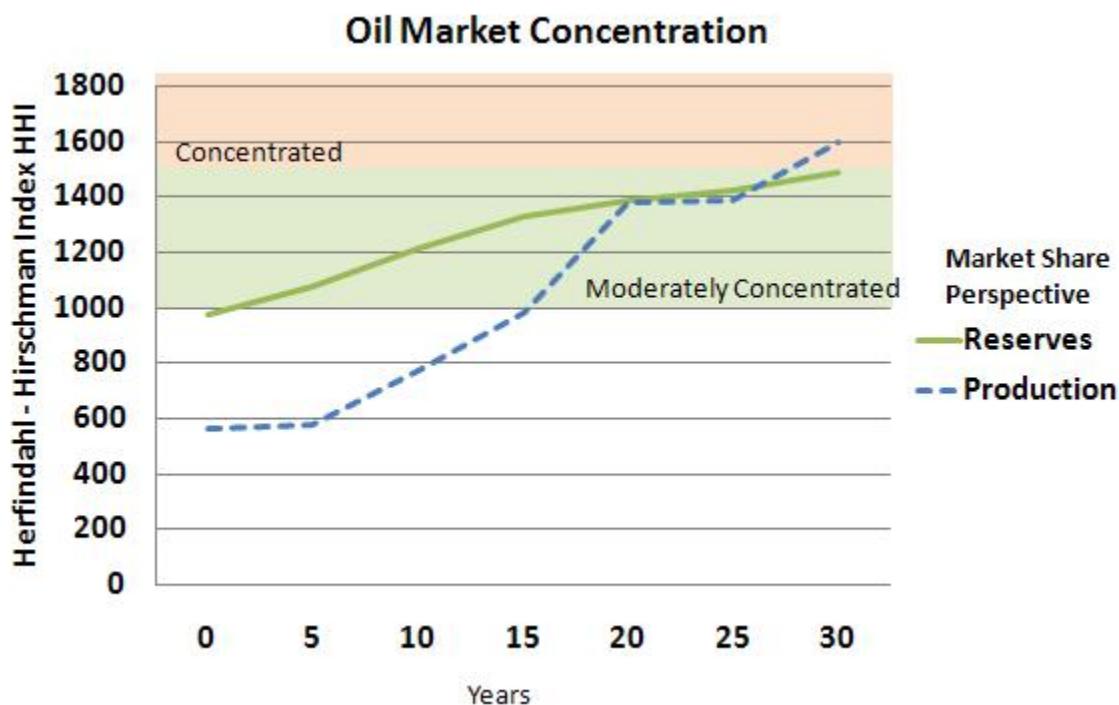


Figure 3. HHI computation for the World Oil Market. Based on U.S. Energy Information Administration 2006 International Figures.<sup>57</sup> All countries are treated as independent actors.

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<sup>57</sup> Energy Information Agency (EIA), "International Energy," U.S. Department of Energy, <http://www.eia.doe.gov/emeu/international/contents.html> (accessed September 15, 2008).

Figure 3 takes the existing energy market, projects into the future using a constant growth factor and depletes reserves in the various countries according to their current production rate. Each country is treated as an independent market shareholder representing all companies within its borders, an assumption that is clearly unrealistic; though the degree of unrealism that it involves varies with political circumstances. Moreover, even if the Organization of the Petroleum Exporting Countries (OPEC) is ignored, Figure 3 shows that the market is consolidating. Obviously, if OPEC is treated as a single block, the scores change substantially to over 5,000 for reserve and over 2,000 for production perspectives. Many factors would realistically change the future as represented in this chart. Price fluctuations, technology, future oil reserve discovery, changes in production capacity, and international conflict are but a few complications which damage this crystal ball. Nonetheless, the measurement is still useful in setting a baseline for comparison to other energy options in terms of market consolidation. Otherwise, analysts are left with subjective impressions or must use more complicated modeling schemes whose assumptions may be even more fragile than those required here.

### **3. Market Actors**

Because the market is consolidating, each actor in the system with a significant market share becomes more influential. As such, the question becomes, who are these actors? Friends or foes? Stable or unstable? As mentioned, OPEC can potentially exert anti-competitive pressure on the oil market. OPEC countries include:<sup>58</sup>

- Algeria
- Iraq
- Qatar
- Angola
- Kuwait
- Saudi Arabia
- Ecuador
- Libya
- United Arab Emirates
- Indonesia
- Nigeria
- Venezuela
- Iran

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<sup>58</sup> Organization of the Petroleum Exporting Countries (OPEC), "Who are OPEC Member Countries?" Organization of the Petroleum Exporting Countries, <http://www.opec.org/library/FAQs/aboutOPEC/q3.htm> (accessed September 15, 2008).

As formidable as this block is, it is worth noting that it has not always succeeded in behaving like a proper cartel. Rivalries and self interest frequently overwhelm OPEC direction, as happened during the 1973 oil crisis and on many lesser occasions since, when one member of OPEC has sought to mobilize the rest in favor of a common policy and failed.<sup>59</sup> Therefore, focus on OPEC alone may fall short of a complete picture. Table 2 brings back the top fifteen countries with respect to oil reserves and considers each with respect to several metrics which may indicate good governance.

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<sup>59</sup> Paul Roberts, *The End of Oil: On the Edge of a Perilous New World*, 1st Mariner Books ed. (Boston: Houghton Mifflin, 2005), 103-105.

Table 2. Top 15 Oil Reserve Countries, National Index Statistics

Country	2007 GDP (\$ Billion) <sup>60</sup>	GDP % Oil <sup>61</sup>	Unempl <sup>62</sup>	GDP/cap (Intl \$ PPP) <sup>63</sup>	Corruption Perceptions Index <sup>64</sup>	Human Development Index <sup>65</sup>	Freedom House Ratings <sup>66</sup> Political Rights	Civil Liberties
Saudi Arabia	381	48%	13%	22,852	3.3	0.81	7	6
Canada	1,436	--	6%	38,614	8.5	0.96	1	1
Iran	285	10%	12%	10,570	2.7	0.76	6	6
Iraq	no data	no data	18-30%	3,600	1.9	no data	6	6
Kuwait	111	no data	2%	39,343	4.8	0.89	4	4
United Arab Emirates	191	27%	2%	37,941	6.2	0.87	6	5
Venezuela	228	32%	9%	12,176	2.3	0.79	4	4
Russia	1,289	20%	6%	14,705	2.5	0.80	6	5
Libya	70	31%	30%	13,593	2.7	0.82	7	7
Nigeria	167	24%	5%	2,028	2.2	0.47	4	4
Kazakhstan	104	--	7%	10,837	2.6	0.79	no data	no data
United States	13,807	--	5%	45,725	7.3	0.95	1	1
China	3,280	--	4%	5,325	3.3	0.78	7	6
Qatar	73	62%	1%	80,638	6.0	0.88	6	5
Mexico	1,022	4%	4%	14,120	3.3	0.83	2	3
Avg OPEC	199.3	33%	10%	\$25,685	3.6	0.77	5.7	5.3
<b>Most Favorable Score</b>					10	1	1	1
<b>Least Favorable Score</b>					0	0	7	7

<sup>60</sup> Data from country profiles compiled from International Monetary fund data for 2007. International Monetary Fund, "World Economic Outlook Database, October 2008," International Monetary Fund, <http://www.imf.org/external/pubs/ft/weo/2008/02/weodata/weoselco.aspx?g=2001&sg>All+countries> (accessed November 8, 2008).

<sup>61</sup> In some cases, data from different fiscal years is used (consistent for that country) or export data is used to determine oil % of GDP when this value was not provided directly. The Economist, "Country Briefings," The Economist Newspaper Ltd, <http://www.economist.com/Countries/index.cfm> (accessed September 15, 2008).

<sup>62</sup> Data from CIA fact book. Differing fiscal years for some countries was used when consistent information was not available. Central Intelligence Agency, "The World Factbook," The Central Intelligence Agency, <https://www.cia.gov/library/publications/the-world-factbook/index.html> (accessed September 15, 2008).

<sup>63</sup> Data from country profiles compiled from International Monetary fund data for 2007. Figures provided in Current International Dollars. Iraq figure measured in dollars taken from economist data, see note 51. International Monetary Fund, *World Economic Outlook Database, October 2008*.

<sup>64</sup> Transparency International, "CPI Table," Transparency International, [http://www.transparency.org/news\\_room/in\\_focus/2006/cpi\\_2006\\_1/cpi\\_table](http://www.transparency.org/news_room/in_focus/2006/cpi_2006_1/cpi_table) (accessed September 15, 2008).

<sup>65</sup> United Nations Development Program, "Country Tables - 2007/2008 Report," United Nations, <http://hdrstats.undp.org/countries/> (accessed September 15, 2008).

<sup>66</sup> Freedom House, "Map of Freedom in the World," Freedom House, <http://www.freedomhouse.org/template.cfm?page=363&year=2008> (accessed September 15, 2008).

The United Nations Human Development Index (HDI) scores incorporate several factors such as literacy, life expectancy, GDP per capita, and a variety of other elements to provide a general rating of a country's development health beyond economics alone. HDI ratings above 0.8 are considered favorable. Transparency International's Corruption Perceptions Index (CPI) is based on expert survey results compiling testimony with regard to bribes, corruption, and transparency. Only 16% of the 163 surveyed countries scored above a seven, with over 50% of countries scoring below four. Average Freedom House ratings above 5.5 are considered "not free" in terms of freedom of expression, political participation, civil liberties, rule of law and other similar measures. In this case, several actors do not score well in terms of corruption or freedom. Analysts who believe that corrupt authoritarian regimes are prone to arbitrary, counterproductive policy decisions have reason to be concerned with these statistics. Even when combining the Freedom House Scores, the poor index scores outnumber the good ones. Remove the HDI, an index influence by GDP and oil revenue, and the balance shifts in favor of poor ratings by over three to one. These ratings may indicate internal problems which may cause security problems in the long run no matter what the relations are with the United States today.

In summary, energy security entails that available alternative energy options meet three requirements. First, options should meet a reduction target of approximately 10 Quad Btu in oil energy production. Secondly, they should provide a market consolidation structure comparatively better than the existing market for oil. And third, control of energy resources should not be disproportionately in the hands of states predisposed to arbitrary or hostile actions at odds with U.S. national security.

## C. CLIMATE CHANGE

The Intergovernmental Panel on Climate Change (IPCC) lays out several scenarios based on the magnitude of greenhouse gas (GHG) concentrations in the atmosphere. Table 3 summarizes these factors.

Table 3. IPCC CO<sub>2</sub> Concentration/Global Warming Scenarios<sup>67</sup>

CO <sub>2</sub> concentration @ stabilization ppm	CO <sub>2</sub> equivalent concentration @ stabilization including all GHG ppm	Change in CO <sub>2</sub> emissions to achieve stabilization level percent	Average temperature increase °C	Average Sea Level Rise meters
350 - 400	445 - 490	-85 - -50	2.0 – 2.4	0.4 – 1.4
400 - 440	490 - 535	-60 - -30	2.4 – 2.8	0.5 – 1.7
440 - 485	535 - 590	-30 - +5	2.8 – 3.2	0.6 – 1.9
485 - 570	590 - 710	+10 - +60	3.2 – 4.0	0.6 – 2.4
570 - 660	710 - 855	+25 - +85	4.0 – 4.9	0.8 – 2.9
660 - 790	855 - 1,130	+90 - +140	4.9 – 6.1	1.0 – 3.7

Experts have divided discussion with regard to emissions targets into a consideration of CO<sub>2</sub> ppm levels at stabilization.<sup>68</sup> 450 ppm is generally the most favorable target with climate concerns given greater weight than economy.<sup>69</sup> However, 550 ppm is generally regarded more affordable economically.<sup>70</sup> Although it may be tempting to move toward the more affordable goal, it is worth considering that this analysis typically understates the economic costs of climate change. This is especially true when researchers begin to take into account the possibility of rapid climate change as global warming pushes the weather system past tipping points from which it cannot recover. Experts examining this problem typically recommend 400 ppm

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<sup>67</sup> Lenny Bernstein and et al., "Climate Change 2007 Synthesis Report: Summary for Policymakers," WMO, IPCC Secretariat, 20.

<sup>68</sup> Dirk Forrister, Rich Rosenzweig and Rob Youngman, *An Assessment of Eleven Countries' Climate Change Performance: A Comparative Evaluation of Environmental, Economic, and Technology Performance* (Washington D.C.: National Commission on Energy Policy, 2004); Union of Concerned Scientists, "A Target for U.S. Emissions Reductions," Union of Concerned Scientists.

<sup>69</sup> Ibid.

<sup>70</sup> Peters and et al., *Stern Review: The Economics of Climate Change*, 1-712; Joseph Aldy, "The IPCC Working Group III Report and some Key Policy Questions," climatepolicy.org, <http://www.climatepolicy.org/?p=39> (accessed September 15, 2008).

or less.<sup>71</sup> This analysis will adopt the 450 ppm target recognizing that to exceed this goal, alternative energy solutions will need to grow appropriately.

How much must the U.S. energy industry change to stabilize the atmosphere at 450 ppm? In 2007, Amy Luers and a team of experts wrote a paper for the Union of Concerned Scientists to address this problem specifically.<sup>72</sup> They suggest that to reach this goal, the United States must reduce emissions by 80 percent by 2050 and constrain cumulative emissions to between 160 and 265 giga-ton carbon-dioxide-equivalent GHG emissions (GtonCO<sub>2</sub>eq) for the time between 2000 and 2050 (by 2005 the total is already 45 GtonCO<sub>2</sub>eq).<sup>73</sup> These targets for emissions reductions are based on different ways of computing the U.S. share the GHG world budget.<sup>74</sup> The 165 Gton limit is based on U.S. share of world population (lower goal), and the 265 Gton limit is based on U.S. share of current GHG emissions (upper goal).

Achieving either of these goals means severely curtailing the cumulative emissions of GHG, 90% of which comes from energy production. Figure 4 provides the EIA reference case cumulative emissions with emissions projections to meet both the lower and upper bounds of the emissions goals to stay below the 450 ppm limit.

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<sup>71</sup> Fred Pearce, *With Speed and Violence: Why Scientists Fear Tipping Points in Climate Change* (Boston: Beacon Press, 2007), 242; J. Hansen et al., "Target Atmospheric CO<sub>2</sub>: Where should Humanity Aim?" (Journal Article, Eprint arXiv:0804.1126; Revised Version Submitted to Open Atmospheric Science Journal, [http://www.columbia.edu/~jeh1/2008/TargetCO2\\_20080407.pdf](http://www.columbia.edu/~jeh1/2008/TargetCO2_20080407.pdf). (accessed September 15, 2008).

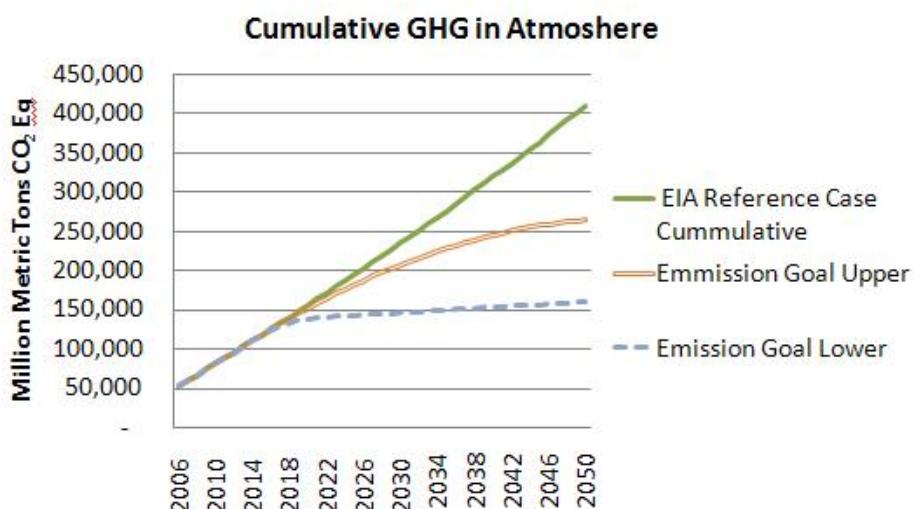
<sup>72</sup> Amy L. Luers et al., *How to Avoid Dangerous Climate Change: A Target for U.S. Emissions Reductions* (Cambridge, MA: Union of Concerned Scientists, 2007).

<sup>73</sup> Ibid.

<sup>74</sup> Ibid.

## Targeting 450 ppm CO<sub>2</sub> eq Concentration

U.S. 2008 EIA Reference Case w/ Suggested U.S. Goals\*



\* A 20% addition was added to EIA CO<sub>2</sub> data because other GHG were not included in the 2008 projection data. 20% is an averaged figure based on 10 years of past EIA data

Figure 4. EIA Reference Case Cumulative Emissions Extrapolation to 2050. Comparison with 450 ppm cumulative goals. This analysis begins with a balance of 45,000 million metric tons in 2005.<sup>75</sup>

Figure 4 represents an extrapolation of the EIA reference case past its 2030 termination using a 10-year growth average to reach the 2050 total emissions goal comparisons. Both upper and lower goal tracks follow the reference case initially allowing time for new strategies to be implemented. Although some energy options may provide an opportunity for an early start, the case above assumes such a radical change will take some time to implement. Even as there are many ways to reach the end states on the graph, it is clear that to meet the lower population-based limit will require a radical change in the near term. The upper limit is more achievable because the change is relatively gradual. Figure 5 shows the extent of the required annual decrease in fossil-fuel-based energy production. Since the lower limit case is so extreme in the early years,

<sup>75</sup> Luers et al., *How to Avoid Dangerous Climate Change*.

the transportation sector energy consumption must be rapidly handled. The figure assumes a hydrogen-based system which carries an energy premium. Although hydrogen-based fuel provides a bonus in mileage, it loses ground in production.<sup>76</sup>

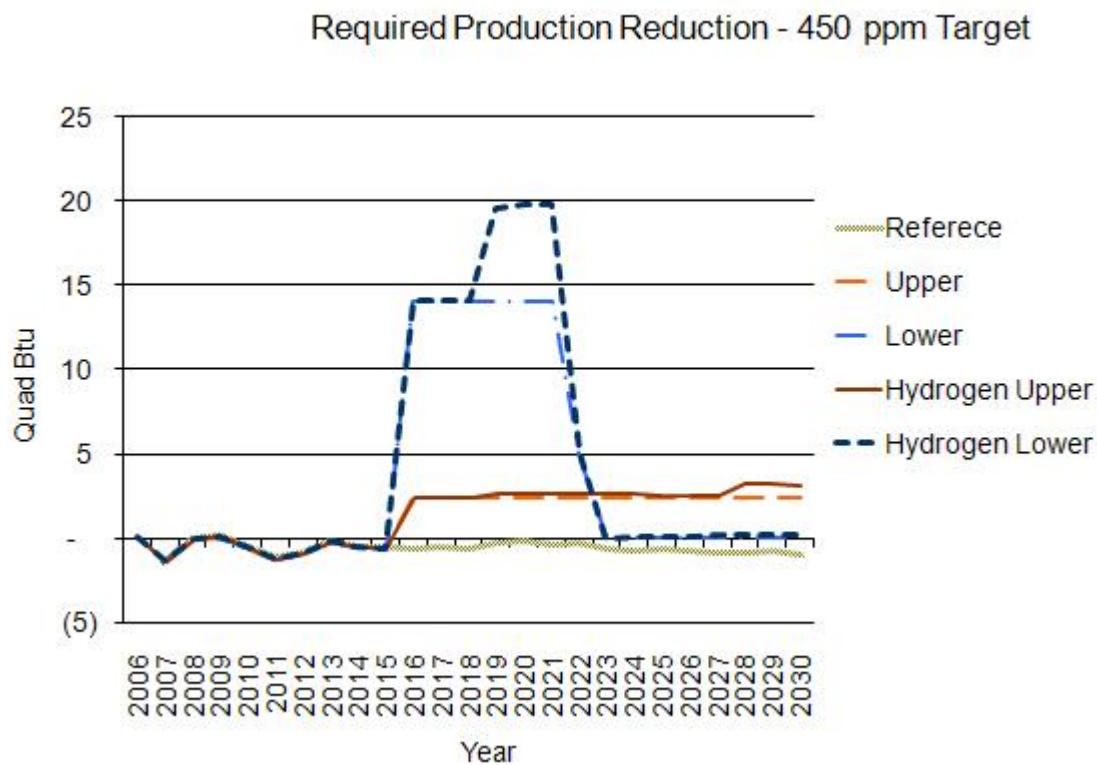


Figure 5. Fossil Fuel Annual Energy Reduction Requirement. Hydrogen scenarios include a power premium to provide for hydrolysis production, but allow for a benefit due to more efficient driving efficiency.

Figure 5 indicates the magnitude of change required to meet climate change goals. There are many other roadmaps to reach these goals, some of which may not include a hydrogen solution. Transportation solutions vary with respect to efficiencies, and there is no room for a detailed analysis of all of these solutions here. A hydrogen-based answer using electrolysis represents a fairly demanding plan, more demanding than other

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<sup>76</sup> Bodansky, *Nuclear Energy: Principles, Practices, and Prospects*, 594.

potential solutions.<sup>77</sup> Each of these alternatives, from bio-fuels and hybrid vehicles to hydrogen fuel cells and full electric vehicles, has its own challenges and inefficiencies. The focus here on electrolysis and hydrogen provides a conservative roadmap with fewer GHG emissions than many other options (especially the use of fossil fuels to produce hydrogen) while accepting that more efficient solutions will provide a lower demand. A electrolysis-hydrogen design will require an additional 2 - 7 Quad Btu capacity. This addition is above the existing Quad Btu demands of the transportation sector already included in the reference case and in the reduction figures. These annual figures, as rough as they are, when contrasted with actual and projected demand figures in Table 4 weigh heavy, even if they are off by several percentage points.

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<sup>77</sup> Michael Wang, "Well-to-Wheels Energy and Emission Impacts of Vehicle/Fuel Systems," Center for Transportation Research, Argonne National Laboratory, <http://www.transportation.anl.gov/pdfs/TA/273.pdf> (accessed October 7, 2008).

Table 4. EIA U.S.<sup>78</sup> and World<sup>79</sup> Energy Demand Projections by Sector and Fuel

Sector	United States		World	
	2005	2030	2005	2030
	(Quad Btu)	(Quad Btu)	(Quad Btu)	(Quad Btu)
<b>Residential</b>	21.6	25.0	96.2	138.0
<b>Commercial</b>	17.9	25.0	69.9	104.9
<b>Industrial</b>	32.8	35.0	205.7	315.9
<b>Transportation</b>	28.0	33.0	90.4	135.7
<b>Total</b>	<b>100.3</b>	<b>118.0</b>	<b>462.2</b>	<b>694.7</b>
<b>Liquids</b>	40.1	44.0	171.9	229.3
<b>Natural Gas</b>	22.3	23.4	109.3	164.7
<b>Coal</b>	22.5	29.9	125.8	202.2
<b>Nuclear</b>	8.2	9.6	27.9	39.5
<b>Renewable</b>	6.3	11.0	36.9	59.0

Thus, it would seem that on one hand the U.S. could be faced with realigning its entire fossil fuel energy sources by 2022 or on the other hand introduce these substantial changes over the next few decades. Because both of these scenarios are fairly large in scope, some have suggested that no single energy solution can handle the transition. This burden sharing of carbon emissions shedding is often described in terms of “stabilization wedges.” Each wedge in this discussion represents a different form of carbon emissions reduction measure from carbon sequestration, conservation, and telecommuting to several energy production changes to include both solar and nuclear options.<sup>80</sup> Stephen Pacala

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<sup>78</sup> Although both breakouts are from the EIA reference case, some differences in rounding and data categorization has cause totals to misalign slightly. Energy Information Agency (EIA), "Total Energy Supply and Disposition Summary," U.S. Department of Energy, <http://www.eia.doe.gov/oiaf/aeo/pdf/appa.pdf> (accessed September 15, 2008).

<sup>79</sup> Although electrical power loss is known in magnitude, it is not provided by sector. The chart uses the U.S. loss proportions by sector to approximate the world loss. Energy Information Agency (EIA), "Reference Case Projections by End-use Sector and Country Grouping Data Tables (2005-2030)," U.S. Department of Energy, <http://www.eia.doe.gov/oiaf/ieo/ieoenduse.html> (accessed September 15, 2008).

<sup>80</sup> Robert Socolow and others, "Solving the Climate Problem: Technologies Available to Curb CO<sub>2</sub> Emissions," *Environment* 46, no. 10 (December 2004), 8-19.

and Robert Socolow propose a wedge combination in a 2004 *Science* magazine article which could serve as a useful starting point.<sup>81</sup> They propose that the nuclear and solar solutions as part of this study would take up five out of fourteen equally sized wedges, around 36% of the total change required. In order for this strategy to work, the carbon capture technologies for coal and natural gas power plants must become effective by 2022, or the burden to be carried by energy options here will double. Another five of these stabilization wedges require the use of more efficient fossil fuel plants and carbon dioxide capture and storage capabilities. This study will use a target of 40% of the transfer illustrated in Figure 5, which would equate to a total change in annual production of between 19 and 40 Quad Btu by 2030.

In summary, the above requirements from the three primary drivers toward alternative energy are:

- OIL PEAK: A need to prepare for a sharp reduction in production capacity and increased oil prices by 2025
- ENERGY INDEPENDENCE: A decrease in oil energy production in the U.S. by 10.6 Quad Btu/yr by 2030
- ENERGY INDEPENDENCE: A market for energy resources more favorable than the current oil market both in terms of market consolidation and in terms of state control
- CLIMATE CHANGE: A solar or nuclear capability to replace approximately 19 – 40 Quad Btu in annual energy production between 2015 and 2030.

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<sup>81</sup> S. Pacala and R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science* 305, no. 5686 (August 13, 2004), 970.

- TRANSPORTATION: In all cases, the transformation of the U.S. transportation system will either be required before the timeframe of this study, or will need to be underway. Part of this demand is included in the climate change goals, but an additional 2 – 7 Quad Btu will be required to account for a demanding electrolysis operation to produce hydrogen without adding significant GHG emissions.

To be sure, meeting the climate change goal will likely exceed the requirements for the first two, but because the last goal is possibly too ambitious for the U.S. economy, it is worth examining which requirements will still be met if this one falls through. It is also worth noting which force is driving what requirement. The requirements for climate change are substantially different from the requirements for energy independence, a distinction easily overlooked.

### **III. ENERGY FUTURES**

#### **A. SCENARIO SCOPE**

To discuss the implications of a push in either direction, solar or nuclear, this analysis must first describe what competing scenarios about the future of energy represent in terms of the types of assets requiring protection and the nature of their demands on resources. The purpose here is to describe what the United States must protect in general. Because the thrust of this study is security, economic concerns are only addressed to the extent that they effect policy options relevant to security. Energy economics will change substantially with policy decisions, changes in supply and demand for different energy resources, changes in transportation costs, and a host of other factors better handled in other studies. What follows is a brief overview of how the demands of Chapter II would be met with either nuclear or solar energy

#### **B. MEETING ENERGY DEMAND**

Before dividing the discussion into the nuclear and solar components, readers should understand that replacing a Quad Btu of fossil fuel energy production may not involve a straightforward exchange. Each energy solution comes with its own energy demands. Experts examine this in a number of ways in order to determine a common metric for purposes of comparison: energy return on investment (EROI). EROI is the ratio of energy produced versus the energy used in the production process, while most people measure energy as the quantity delivered to customers. This EROI ratio also captures the energy consumed along the way, in the process of plant construction, mining, drilling, shipping etc. Table 5 provides a summary of expert estimates of EROI for various energy solutions. The most desirable energy options would have high EROI ratios, producing significantly more energy than consumed.

Table 5. Reported Energy Return on Investment Values

Energy Source	EROI	% 2006 Energy Production <sup>82</sup>
<b>Processed Liquid Fuel (Gasoline, 2000)<sup>83</sup></b>	<b>10</b>	<b>40%</b>
<b>Coal (2000)<sup>84</sup></b>	<b>5</b>	<b>23%</b>
<b>Delivered Natural Gas<sup>85</sup></b>	<b>5</b>	<b>22%</b>
<b>Hydro w/reservoir<sup>86</sup></b>	<b>205</b>	<b>3%</b>
<b>Corn Ethanol<sup>87</sup></b>	<b>1.24</b>	<b>0.5%</b>
<b>Nuclear<sup>88</sup></b>	<b>16</b>	<b>8%</b>
<b>Solar PV<sup>89</sup></b>	<b>10</b>	<b>0.01%</b>
<b>Solar Thin Film PV<sup>90</sup></b>	<b>7.5</b>	<b>-</b>
<b>Solar CSP<sup>91</sup></b>	<b>72</b>	<b>0.03%</b>
<b>Wind<sup>92</sup></b>	<b>30</b>	<b>0.26%</b>

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<sup>82</sup> Assumes 99% transportation is gasoline and that the proportion of this demand consumed as diesel has a comparable EROI. Energy Information Agency (EIA), *Annual Energy Outlook, 2008*.

<sup>83</sup> Cutler J. Cleveland, "Net Energy from the Extraction of Oil and Gas in the United States," *Energy* 30 (2005), 781.

<sup>84</sup> L. Gagnon, "Life Cycle Assessments Confirm the Need for Hydropower and Nuclear Energy," <http://www.osti.gov/servlets/purl/839326-jpdcFb/native/>; File transfer mode: application/pdf.

<sup>85</sup> Delivered 1,250 miles. Ibid.

<sup>86</sup> Ibid.

<sup>87</sup> Hosein Shapouri, James A. Duffield and Michael S. Groboski, *Estimating the Net Energy Balance of Corn Ethanol* (Washington D.C.: U.S. Department of Agriculture, 1995).

<sup>88</sup> Gagnon, *Life Cycle Assessments Confirm the Need for Hydropower and Nuclear Energy*, Americas Nuclear Energy Symposium (ANES 2004), Miami, FL, 4.

<sup>89</sup> Value for standard conditions. Office of Energy Efficiency and Renewable Energy, "What is the Energy Payback for PV?" U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, <http://purl.access.gpo.gov/GPO/LPS48749>; <http://purl.access.gpo.gov/GPO/LPS48749>.

<sup>90</sup> Value for standard conditions. Ibid.

<sup>91</sup> Assumed 30-yr lifespan for CSP plant. Favorable conditions. Solar Energy Technologies Program, *Concentrating Solar Power* (Golden, CO: National Renewable Energy Laboratory, 2008), [http://solareis.anl.gov/documents/docs/NREL\\_CSP\\_1.pdf](http://solareis.anl.gov/documents/docs/NREL_CSP_1.pdf) (accessed October 7, 2008).

<sup>92</sup> Value taken for favorable conditions. Ida Kubiszewski and Cutler J. Cleveland, "Energy Return on Investment (EROI) for Wind Energy" In *Encyclopedia of Earth*, ed. Cutler J. Cleveland, 2008th ed. (Washington D.C.: Environmental Information Coalition, National Council for Science and the Environment, 2008), 1.

Before considering the statistics in Table 5, one should first understand the limitations of this type of simplification. First of all, these figures are frequently based on the locations of existing supply. The EROI of a solar plant in Alaska will be vastly different from a plant in the desert. The EROI of natural gas will change significantly depending on storage and shipping requirements. Coal can change drastically depending on location and transport needs. EROI data is in such respects inherently speculative, laden with controversy, and at times tainted with advocacy. These facts do not detract from the importance of this measurement as part of energy policy analysis. Energy strategists should reject any solution which does not produce significantly more energy than it consumes. One does not build a store that only sells to its employees. As this debate matures, one would expect EROI data to become more refined, and this analysis should be revised appropriately. For this effort, these figures provide a rough scope for security discussion. The intent is not to propose an optimal solution, just a possible one with enough accuracy to allow security issues to be addressed credibly.

Accepting the shortcomings of these numbers, EROI can be used to represent a baseline of existing system efficiency. Using the EROI figures and percentages of existing production, this examination will use an EROI of 14 to represent the starting EROI for the reference case, and 6.25 to represent fossil fuel systems to be replaced. For example, 10 Quad Btu of fossil fuel production will consume 1.7 Btu of energy. If the choice for replacement is in Solar Concentrated Solar Plant (CSP) production, with an EROI of 72, the new system need only provide around 8.5 Quad Btu to be comparably effective. Equation 1 can be used to make any number of comparisons.

$$[\text{Old Production}] - \frac{[\text{Old Production}]}{[\text{EROI}_{\text{old}}]} = [\text{New Production}] - \frac{[\text{New Production}]}{[\text{EROI}_{\text{new}}]}$$

Equation 1.

Calculation for Energy Option Replacement.

The target for this chapter is to provide a rough approximation of the magnitude of the systems required to make the changes requested in Chapter II so that the study can move on to security criteria with scenarios which account for the power demands of the solutions themselves, a distinction which places limits on the feasibility of options, at least in the short run. EROI points the examination toward energy solutions which can provide more bang for each Btu.

## C. NUCLEAR FUTURE

Painting a picture of a nuclear future requires answers for two key questions. First, what facilities are required to meet the new demands? Second, what are the key resources required for these facilities to provide the power? For the most part, these predictions will be based on existing technology. Analysis based on speculation of unproven (although promising) systems will add to the uncertainty in these projections which already bear many assumptions.

### 1. Nuclear Plant Requirement

The United States already possesses a robust nuclear power production capability. The 104 plants produce 8.21 Quad Btu of energy every year, 8% of the total primary energy market.<sup>93</sup> They meet this demand with just over 99,000 MWe in plant capacity (~12,000 MWe per Quad Btu). The U.S. nuclear plant inventory consists of mostly boiled water reactors (BWR) and pressurized water reactors (PWR), both traditional proven designs which have been around for decades. These reactor types and their variants make up for over 85% of the world reactor inventory.<sup>94</sup> Table 6 provides a plant requirement for the reduction goals in Chapter II based on existing plant efficiencies, and a standard 1,000 MWe future plant capacity.

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<sup>93</sup> Energy Information Agency (EIA), "U.S. Nuclear Reactor List," U.S. Department of Energy, [http://www.eia.doe.gov/cneaf/nuclear/page/nuc\\_reactors/operational.xls](http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/operational.xls) (accessed September 15, 2008).

<sup>94</sup> See Appendix with World Nuclear Association Data.

Table 6. Nuclear plant requirements to meet reduction goals

Goal	Reduction Requirement					# 1,000 Required By
	Fossil Fuel (Quad Btu)	Nuclear (Quad Btu)	Required Capacity*	MWe Plants		
EROI	6.25	16.00				
Energy Independence	10.6	9.5	115,000	115	2030	
Emission Upper**	19.0	17.4	210,000	210	2030	
Emissions Lower	40.0	36.6	442,000	442	2022	
Addition for Hydrogen Upper	2.0	1.8	22,000	22	2030	
Addition for Hydrogen Lower	7.0	6.4	77,000	77	2022	
Total Emissions Upper	21.0	19.2	232,000	232	2030	
Total Emissions Lower	47.0	43.0	519,056	519	2022	

\*Use existing MWe/Quad Btu ratio: 12,084

Nuclear GHG Emissions = 2% of fossil fuel emissions so a slight penalty is applied to the Nuclear Requirement:<sup>95</sup> 1.02

Table 6 highlights a few key challenges with the reduction goals. Energy independence requires more than twice today's nuclear capability by 2030. For the United States to do its part to restrict the atmosphere to 450 ppm CO<sub>2</sub>Eq GHG concentration, the nation will have to drastically change. The upper goal, based on current GHG contribution, will require a tripling of today's capacity if a hydrogen electrolysis system is included. The most drastic change is a GHG reduction based on U.S. population. The lower goal will require nearly six times the current capacity by 2022. Using an optimistic \$2-billion cost figure (assuming savings with standardized designs), this amounts to well over a trillion dollars within the next 14 years.<sup>96</sup> How

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<sup>95</sup> Nuclear Energy Institute, "Comparison of Lifecycle Emissions," Nuclear Energy Institute, [http://www.nei.org/filefolder/UWM\\_-\\_Chart\\_on\\_Comparison\\_of\\_Life-Cycle\\_Emissions.ppt#258,1](http://www.nei.org/filefolder/UWM_-_Chart_on_Comparison_of_Life-Cycle_Emissions.ppt#258,1), Comparison of Life-Cycle Emissions Tons of Carbon Dioxide Equivalent per Gigawatt-Hour (accessed September 15, 2008).

<sup>96</sup> Current cost estimate for various plants range from \$2.6 - \$4.5 billion depending on size and location. Part of these higher price tags come from the custom designs for each plant. This effort will likely require a standardized design and the creation of a streamlined industry. BBC News, "Q&A: The Costs of Nuclear Energy," *BBC News*, sec. Business, January 10, 2008; Shankar Vedantam, "Uncertainties Slow Push for Nuclear Plants," *Washington Post*, sec. Politics, July 24, 2005.

significant is this requirement? The EIA reference case includes macroeconomic indicators which plug into its data to build its forecasts. In the fourteen years leading up to the most rigid 2022 deadline, the real investment component of GDP for all of those year will total around \$31 Trillion. Government spending will amount to around \$30 million. A trillion-dollar investment represents over 1.5% of all government spending plus all investment in the United States. This would be 0.5% of the U.S. Real GDP, a cost comparable to that currently being attributed to the wars in Iraq and Afghanistan.<sup>97</sup> Even if future innovations cut this cost in half, the shift represents a major undertaking. As mentioned, Table 6 represents a future using the current mix of reactor types. Experts must also determine whether such a mix is sustainable considering demand for a critical resource for nuclear energy, uranium.

## **2. Nuclear Resource Requirement: Demand and Availability**

Although nuclear power requires many types of resources, uranium is the critical component. Much like oil, uranium is a finite resource the reserves of which are not known exactly, but many estimates cause “peak oil”-like concern when projecting energy demand into the future. Figure 6 represents projects the EIA reference case into the future with additional predictions based on the U.S. changes required in this study as well as a projection based on how demand were to change if the rest of the world went in the same direction.

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<sup>97</sup> Jim Lobe, "U.S.-Report: Wars in Iraq, Afghanistan may Cost \$3.5 Trillion," *Global Information Network* (November 14, 2007), 1.

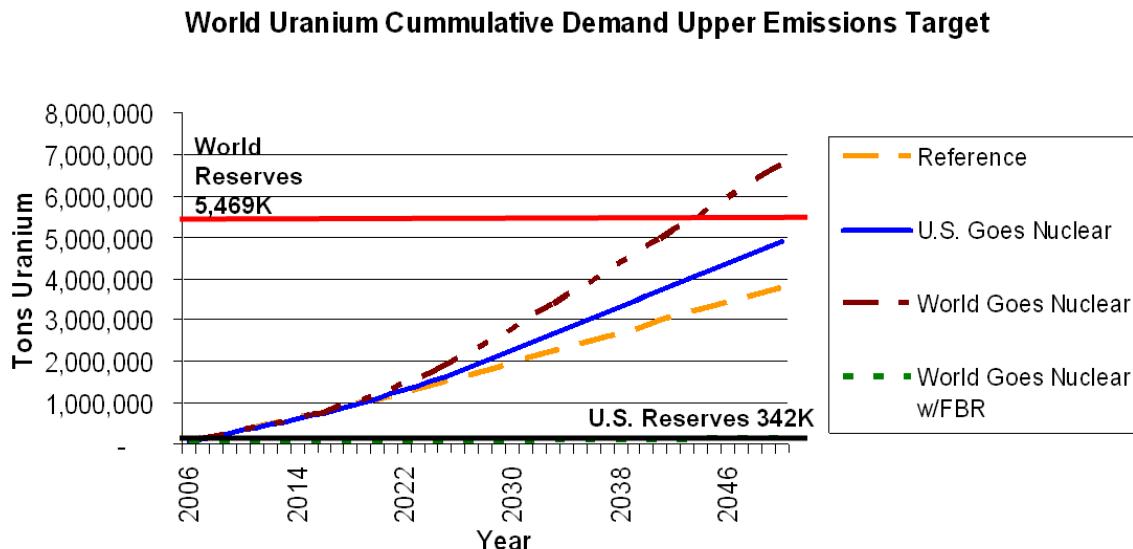


Figure 6. Cumulative uranium demand to meet the 450 ppm GHG concentration goal shifting 40% energy demand toward nuclear power. Reserves figures assume a \$130/kg U extraction cost.<sup>98</sup>

Figure 6 is useful to make a couple of key points. First, even as estimates of reserves may change, the traditional mix of reactors will lead to a serious depletion of cheaply accessible uranium before the turn of the century. In some cases, the supply may dry up before the new plants payback the cost of the investment in their construction. However, the reserves estimates in Figure 6 are bounded by the economics of uranium extraction, and estimates which ignore this constraint have exceeded 35 million tons. Such estimates would certainly buy time for nuclear power to make a difference, but part of the reason for the economic boundaries is the extra effort to perform the extraction. One could imagine that mining hard-to-reach reserves would change the EROI picture that warranted the move toward nuclear power in the first place. As such, the time bought by expensive reserves will possibly come at a significant cost in terms of both funds and energy.

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<sup>98</sup> World Nuclear Association, "Supply of Uranium," World Nuclear Association, <http://www.world-nuclear.org/info/inf75.html> (accessed September 02, 2008).

A search for a better solution leads analysts to the second key point with regard to Figure 6. Instead of using a traditional mix of reactors, one could project demand based on the use of Fast Breeder Reactors (FBR). This reactor type has already been constructed in several countries, and more plants are planned. Two FBR plants are in operation today, one in Russia and one in France.<sup>99</sup> Figure 6 provides a projection based on FBR reactors handling the load with a uranium demand of one fiftieth the demand from traditional reactors.<sup>100</sup> This is possible because a FBR reactor produces fissionable plutonium as part of its process. It produces more fuel than it consumes.

The use of FBR as part of this study presents a couple of problems. First, although these reactors have been constructed, their lifecycle efficiencies are unknown. What EROI value is appropriate for an FBR? Considering the difficulties with estimating traditional reactor types, any value provided today would invite just criticism. Table 5 suggests a value of 16 for today's reactor mix, but this is widely disputed, as recognized within the referenced study from which the value was taken.<sup>101</sup> FBR plants are more complex but generate less waste.<sup>102</sup> However, as this is a security study, the goal is to determine what systems will serve in solving the energy problems, and roughly to what degree will they be deployed. Figure 6 indicates that FBR will be a likely part of any nuclear solution, and the analysis should review the security implications of such a move. Because these reactors are more complex, they will likely cost more, magnifying the investment challenges mentioned earlier.

In summary, a nuclear push to meet the demands of the various goals in this study will involve between 100-600 new nuclear power plants in the United States, a significant proportion of which will likely be FBR plants. The following chapters will examine the security dilemmas posed by this change in terms of resource access, nuclear weapons proliferation, and infrastructure protection.

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<sup>99</sup> World Nuclear Association, "Reactor Database," <http://www.world-nuclear.org/rd/rdsearch.asp> (accessed September 03, 2008).

<sup>100</sup> Ibid.

<sup>101</sup> Gagnon, *Life Cycle Assessments Confirm the Need for Hydropower and Nuclear Energy*, 4.

<sup>102</sup> Bodansky, *Nuclear Energy: Principles, Practices, and Prospects*, 189.

#### **D. SOLAR FUTURE**

Charting a solar course for the United States will involve a larger variety of technologies, more than can be covered in this thesis. This report will resist the temptation to speculate on technologies that are still on the verge of breakthrough to technical and commercial feasibility, and focus instead on systems that have a track record of performance. However, some license will be required to map this future, because deployment of solar power on the scales required here will demand infrastructure solutions that have yet to be proven, namely solutions for energy storage. Additionally, the existing solar energy sources use here represent less than a percent of the current U.S. energy production. Extrapolating these systems to cover the demand required will involve much more uncertainty than in the nuclear case, because the required shift in scale necessarily incorporates more imponderables, whose consequences cannot be realistically anticipated.

The energy goals set forth in Chapter II provide additional reason to pare down the list of solar energy strategies to those technologies that do not involve significant GHG emissions. As such, the following pages will examine a future for solar energy that includes Photovoltaic (PV) Solar Cells, Concentrated Solar Power (CSP), and Wind Energy. This assumes the potential for hydro-electricity is fairly tapped out in the U.S. in terms of large dam projects. Bio-fuels have been rejected because of their low EROI ratings and comparatively high emissions. Wave energy is generally untested. This is not to say that there is no potential for these technologies. It is simply a matter of confining analysis in ways that reduce the amount of speculation required, and so keeping the study both credible and manageable.

The EROI data in Table 5 reflects the performance of solar systems as they plug into existing grids without accounting for the need to store energy at night (or when winds are low). On one hand, since solar energy will only make up for a portion of energy production using the energy independence or stabilization wedge strategy, one could speculate that solar power would handle the daytime energy load, and other power sources could handle the load at night. Although wind energy does not struggle with a

day/night cycle as do energy sources derived from direct sunlight, it does come with its own cycles of lows and highs, prompting a need for energy storage to promote stable service. Presently, the utility companies do have plants which are designed to service peak daytime loads only versus base loads which persist at all hours.<sup>103</sup> Many see solar power as a natural fit for peak or intermediate load capacity.<sup>104</sup> Unfortunately, the required data to test this potential is not available, a limitation that diminishes the fidelity of solar predictions as compared with the nuclear case, but does not hinder this discussion on security considerations. Will peak power capacity concentration completely alleviate the need for energy storage? Certainly not when it comes to transportation demand, a sector for which this project has already built a scenario. But even for electricity, it is probably not a safe assumption. So, if a storage capability is required, how does this affect solar's EROI ratings? This question is for other research projects to answer. P. Denholm and R. Margolis assume a 75% round trip efficiency for existing storage technologies in their computations of per-capita solar footprint requirements for the United States for the National Renewable Energy Laboratory.<sup>105</sup> This value is applied to solar EROI for a 70% energy storage requirement also provided in the same study.<sup>106</sup> Because all of these energy sources are intermittent, this analysis will apply a reduction factor across the board to solar EROI values of -18%.

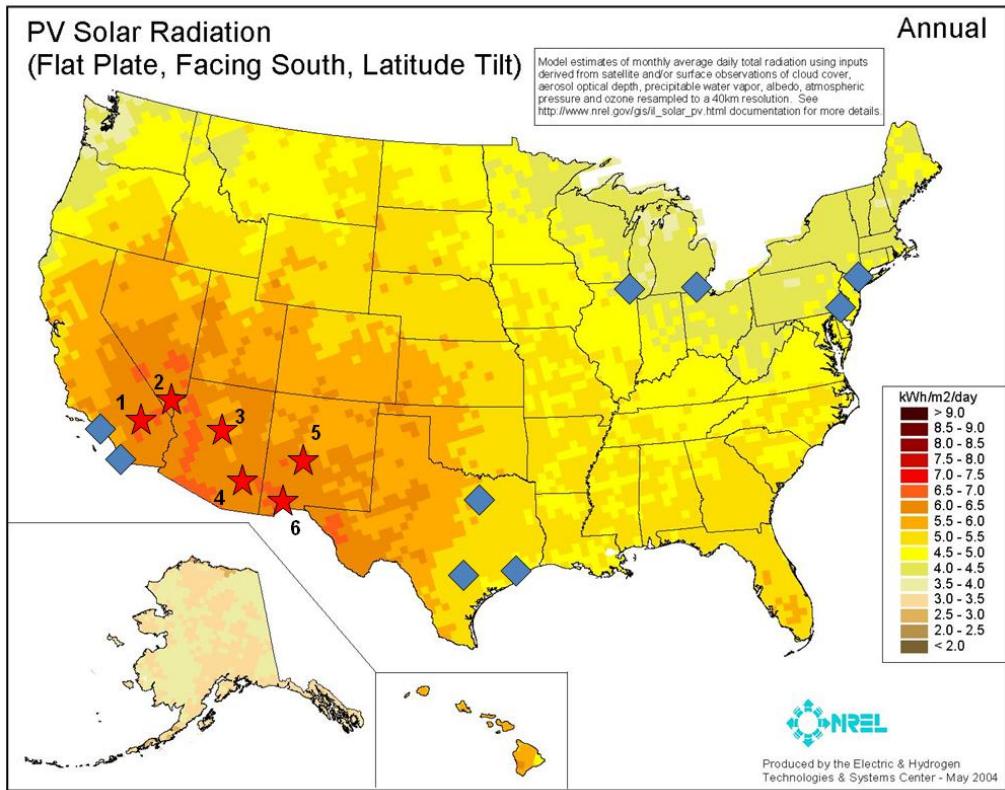
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<sup>103</sup> Energy Information Agency (EIA), "Overview - Generating Capability/Capacity," U.S. Department of Energy, <http://www.eia.doe.gov/cneaf/electricity/page/prim2/chapter2.html> (accessed October 17, 2008).

<sup>104</sup> Bradford, *Solar Revolution: The Economic Transformation of the Global Energy Industry*, 129.

<sup>105</sup> P. Denholm and R. Margolis, *The Regional Per-Capita Solar Electric Footprint for the United States* (Golden, Colorado: National Renewable Energy Laboratory, 2007).

<sup>106</sup> Ibid.



★ NREL proposed CSP site – considering grid, slope, environmental restrictions      ♦ Top-10 U.S. City

Figure 7. NREL map showing PV Solar Radiation.<sup>107</sup> U.S. City location added with CSP site location from NREL presentation considering several constraints restricting site use.<sup>108</sup>

Another complication with EROI data comes from the need to adjust the power grid to accommodate potential concentration of power generation in remote areas for CSP and wind power. Presently, there are 9,351 power plants distributed throughout the country.<sup>109</sup> The EROI in Table 5 assumes favorable conditions, which only exist in

<sup>107</sup> National Renewable Energy Laboratory, "PV Solar Radiation Map," National Renewable Energy Laboratory, [http://www.nrel.gov/images/us\\_pv\\_annual\\_may2004.jpg](http://www.nrel.gov/images/us_pv_annual_may2004.jpg) (accessed October 20, 2008).

<sup>108</sup> Mark S. Mehos, "Overview of the 1000 MW CSP Southwest Initiative" (Portland, Oregon, National Renewable Energy Laboratory, Solar Thermal Electric International Project Development Forum, July 13, 2004).

<sup>109</sup> Energy Information Agency (EIA), "Existing Capacity and Planned Capacity Additions at U.S. Electric Utilities by Energy Source, 2000," U.S. Department of Energy, <http://www.eia.doe.gov/cneaf/electricity/ipp/html1/t1p01.html> (accessed October 17, 2008).

certain parts of the country for Wind and CSP. The CSP figures are based on plants constructed in California, Arizona, and Nevada. The Wind EROI was computed based on agreeable wind conditions in the Northeastern United States. The maps provided in Figures 7 and 8 provide a rough approximation of where these favorable conditions are.

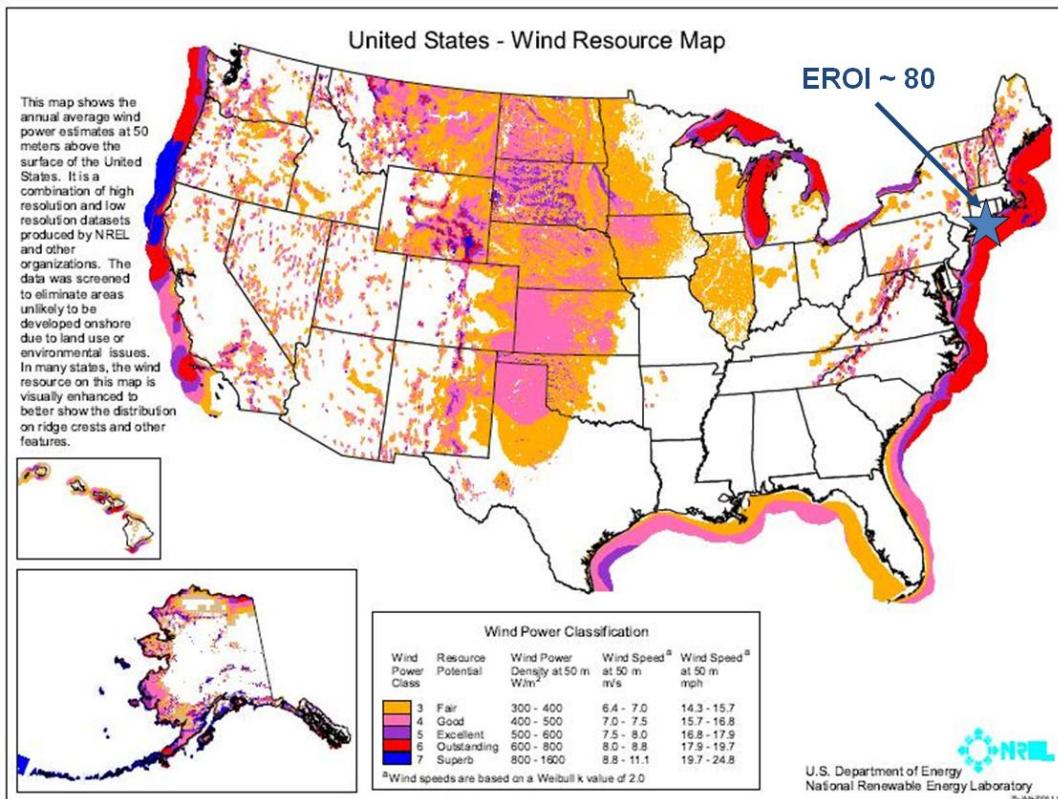


Figure 8. NREL map showing wind resource locations at 50 meter above ground.<sup>110</sup> EROI figure added from Gagnon study.<sup>111</sup>

To account for the inefficiencies in the rest of the country one can build two cases. First, these systems could be deployed everywhere. Second, they could be deployed where conditions are favorable, and power transmission lines will carry the load to the customers along high voltage direct current (HVDC) lines. HVDC lines lose 3% of

<sup>110</sup> National Renewable Energy Laboratory, "United States - Wind Resource Map," National Renewable Energy Laboratory, [http://www.windpoweringamerica.gov/pdfs/wind\\_maps/us\\_windmap.pdf](http://www.windpoweringamerica.gov/pdfs/wind_maps/us_windmap.pdf) (accessed October 20, 2008).

<sup>111</sup> Gagnon, *Life Cycle Assessments Confirm the Need for Hydropower and Nuclear Energy*, 4.

transmitted power per 1,000 km as compared to 8% for traditional AC technology.<sup>112</sup> The U.S. power grid has been known to suffer total transmission line losses of up to 4.32% of total delivered power.<sup>113</sup> Consider the hypothetical case where all U.S. power might come from CSP locations near those proposed in Figure 7 and wind power locations along the coasts where conditions are favorable. Since wind energy is already taxing the existing grid, one might assume such realignment may require the construction of new line capacity.<sup>114</sup> Transmitting energy loads to each state may result in a net power loss of between 2 and 6% depending on how much of this transmission will occur over the existing grid versus HDVC lines.<sup>115</sup> A related problem with this picture is the additional grid construction required to make this idea work. How will this effort be reflected in the EROI assumptions? Unfortunately, there are no available studies that even begin to answer this question. Since these penalties are not as great as those that would apply if CSP or wind were deployed in sub-optimal locations, readers can use this scenario to construct a defensible, yet optimistic vision for solar power with respect to CSP and wind. To be conservative, this analysis will apply a 5% penalty.

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<sup>112</sup> Asian Development Bank, *Guidelines for Estimating Asian Development Bank (ADB) Investments in Renewable Energy and Energy Efficiency Projects* (Manila, Philippines: Asian Development Bank, 2008), <http://www.adb.org/Documents/Clean-Energy/Guidelines-Estimating-ADB-Investments.pdf> (accessed September 20, 2008).

<sup>113</sup> U.S. Climate Change Technology Program, *U.S. Climate Change Technology Program: Technology Options for the Near and Long Term* (Washington D.C.: U.S. Climate Change Technology Program, 2005).

<sup>114</sup> Matthew L. Wald, "Wind Energy Bumps into Power Grid's Limits," *New York Times*, August 27, 2008.

<sup>115</sup> This range was computed using a rough comparison of the EIA state breakdown of delivered power with a 100-mile line loss on a traditional grid versus a loss over 100-1,500 miles depending on the state proximity to a favorable CSP or wind location. Energy Information Agency (EIA), "State Electricity Profiles," U.S. Department of Energy, [http://www.eia.doe.gov/cneaf/electricity/st\\_profiles/e\\_profiles\\_sum.html](http://www.eia.doe.gov/cneaf/electricity/st_profiles/e_profiles_sum.html) (accessed October 20, 2008).

To conclude, the EROI figures to include both adjustments for storage (18%) and grid changes (5%) are as follows:

- Solar PV: 8
- Solar CSP: 56
- Wind: 23

The next challenge in drawing this solar picture is the dividing the future power load between the three energy types. To keep this simple, let's divide the load based on EROI and test these proportions against available capacity. Using EROI, one would expect 64% CSP, 27% wind, and 9% PV. The next question will be to determine whether or not these technologies can meet these demands.

The following sections show the solar power future as divided between the different solar technologies to cover each requirement. Each part includes the specific reduction goals as well as demand on key resources. This analysis examines existing plants and products already on the market. Other technologies may require different resources which would alter the resource availability picture depending on which technology finally wins out. Each chart uses a ratio of existing MWe capacity versus existing Quad Btu output to extrapolate existing capacity to meet new demand. As such, the numbers include the inefficiencies of today's alternative energy market. This would be a conservative assumption, but the only reasonable way to build an estimate without building scenarios based on unproven technologies or exploratory analysis beyond the scope of this study.

## **1. Concentrated Solar Power (CSP)**

CSP plants will provide the lion's share of power in this strategy due to their favorable EROI in the southwestern desert region. Table 7 summarizes these requirements.

Table 7. CSP Requirements to Meet 64% of the Reduction Goals – power production requirements only

Goal	Fossil Fuel (Quad Btu)	CSP Production (Quad Btu)*	Land Required (Sq Mile) <sup>116</sup>	6mm Glass Required (tons)	Required By
Proportion		64%			
Adjusted EROI	6.25	56.1			
Existing Annual U.S. Production		0.030		20 million <sup>117</sup>	
Energy Independence	10.6	5.9	630	7.9	2030
Emission Upper**	19.0	10.6	1,130	14.2	2030
Emissions Lower	40.0	22.3	2,379	29.9	2022
Addition for Hydrogen Upper	2.0	1.1	119	1.5	2030
Additional for Hydrogen Lower	7.0	3.9	416	5.2	2022
Total Emissions Upper	21.0	11.7	1,249	15.7	2030
Total Emissions Lower	47.0	26.2	2,795	35.1	2022

\*Use Existing MWe/Quad Btu Ratio:13,637

\*\*Wind/CSP GHG Emissions = 2% of fossil fuel emissions so a slight penalty is applied:<sup>118</sup>1.02

Keep in mind, Table 7 provides a rough estimate of resources for the plant capacity only. To adopt this strategy, U.S. utility companies must implement staggering changes to the power grid, the details of which will require further study. Although grid changes represent a significant cost, the impact is not likely to cause a resource shortage, or cripple any particular market. Some solar critics have complained about the need for land and glass to make solar power work.<sup>119</sup> These problems do not appear to impede CSP as estimated here. Even the most extreme case requires a land area of less than 3%

<sup>116</sup> Used 5 acre/GW planning factor in: Solar Energy Technologies Program, *Concentrating Solar Power* (Golden, CO: National Renewable Energy Laboratory, 2008), [http://solareis.anl.gov/documents/docs/NREL\\_CSP\\_1.pdf](http://solareis.anl.gov/documents/docs/NREL_CSP_1.pdf) (accessed October 7, 2008).

<sup>117</sup> Energy Information Agency (EIA), "Economic Profile and Trends: Glass Industry Analysis Brief," U.S. Department of Energy, <http://www.eia.doe.gov/emeu/mecs/iab/glass/page1b.html> (accessed October 20, 2008).

<sup>118</sup> Nuclear Energy Institute, *Comparison of Lifecycle Emissions*.

<sup>119</sup> Hayden, *The Solar Fraud: Why Solar Energy Won't Run the World*, 187-205.

of the state of Arizona, one of several states in the southwest that could support such plants. The need for glass in total does not compare to the annual domestic glass production in the United States.

The U.S. Department of Energy indicates that the cost for installed CSP capacity is approximately \$3-3.5 per Watt. For the scenarios above costs would range from \$300-1,250 Billion in plant capital construction costs, a sizeable investment even considering that the investment can span several years. This venture will contribute to the sizeable solar investment discussed in the GDP review below.

## **2. Wind Power**

Table 8 provides an approximation of wind power requirements. Land is the key resource for this option to work. Although the land requirements are fairly demanding, especially in the case of the lower emissions goal with hydrogen, a couple of factors will mitigate this impact. First, much of this requirement is for the space between turbines, which is why the additional column is provided to show actual system footprint. So, the energy independence goal will require around 9,000 square miles, but only 300 square miles will consist of the turbines themselves, the rest of the land can be used for other purposes provided the uses do not interfere with the flow of air to those turbines. Second, a significant amount of wind energy is available off shore. This location, although expensive to develop, may still prove cost-effective when considering competition with other land uses. Additionally, off shore units can be larger and take advantage of higher winds to keep the system active. Larger units will require less land per unit capacity.

The concrete and steel requirements to build thousands of wind turbines may seem significant, but readers should keep in mind that the figures in the chart are for the total construction effort, an effort which should span several years ending in 2022 or 2030 depending on which goal the U.S. is building toward. The chart provides the U.S. annual production for cement and steel for comparison. The totals are comparable to an annual production figure, but the impact is likely to remain economic, due to production capacity, and not a result of depletion of reserves as in the case of oil or uranium.

Additionally, many components are recyclable, giving the simpler resource and technological demands of wind energy an advantage over more complex solutions or those which consume resources permanently.

Table 8. Wind requirements to meet 27% of the reduction goals – power production requirements only

Goal	Wind Production (Quad Btu)	# 1.5 MWe* Turbines (EA)	Total Land Demand (Sq Mile) <sup>120</sup>	Wind Turbine Footprint (Sq Mile) <sup>121</sup>	Cement (million tons) <sup>122</sup>	Steel (million tons)	Required By
<b>Proportion</b>	27%						
<b>Adjusted EROI Existing Annual U.S. Production</b>	<b>23.37</b>						
	<b>0.259</b>				<b>98<sup>123</sup></b>	<b>98.2<sup>124</sup></b>	
<b>Energy Independence</b>	<b>2.5</b>	75,000	9,000	300	5.8	3.4	<b>2030</b>
<b>Emission Upper**</b>	<b>4.5</b>	135,000	16,000	600	10.5	6.1	<b>2030</b>
<b>Emissions Lower</b>	<b>9.5</b>	284,000	33,000	1,200	22.0	12.9	<b>2022</b>
<b>Addition for Hydrogen Upper</b>	<b>0.5</b>	14,000	2,000	100	1.1	0.6	<b>2030</b>
<b>Additional for Hydrogen Lower</b>	<b>1.7</b>	50,000	6,000	200	3.9	2.3	<b>2022</b>
<b>Total Emissions Upper</b>	<b>5.0</b>	149,000	17,000	600	11.6	6.8	<b>2030</b>
<b>Total Emissions Lower</b>	<b>11.2</b>	334,000	38,000	1,300	25.9	15.2	<b>2022</b>

\*Use Existing MWe/Quad Btu Ratio: **44,627**

\*\*Wind/CSP GHG Emissions = 2% of fossil fuel emissions so a slight penalty is applied: **125 1.02**

The Department of energy prices wind turbine capacity at around \$1,800 kW.<sup>126</sup> This would drive an investment of between \$200-900 Billion to build winds contribution to the solar vision. This does not include land costs or the cost of the grid adjustments to

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<sup>120</sup> Using the land requirements set forth in the NREL study as a model. National Renewable Energy Laboratory, "20% Wind Energy by 2030 Increasing Wind Energy's Contribution to U.S. Electricity Supply," U.S. Dept. of Energy, Energy Efficiency and Renewable Energy, 10.

<sup>121</sup> Ibid.

<sup>122</sup> Concrete and steel requirement also modeled after NREL study. Ibid., 63.

<sup>123</sup> United States Geological Survey (USGS), "Commodity Statistics and Information," <http://minerals.usgs.gov/minerals/pubs/commodity/> (accessed October 21, 2008).

<sup>124</sup> Ibid.

<sup>125</sup> Nuclear Energy Institute, *Comparison of Lifecycle Emissions*.

<sup>126</sup> National Renewable Energy Laboratory, *20% Wind Energy by 2030 Increasing Wind Energy's Contribution to U.S. Electricity Supply*, 95.

support the changed power production structure. There are a few state level studies which indicate that the grid changes will cost between 7-10% of the \$1,800/kW investment. Ramping up to a nation-wide scope would increase the transmission line requirements, but introduce economy of scale. Using a 10% factor, this would equate to between \$20 - 90 Billion in added costs to modify the grid. Again, as these costs accumulate, the bill becomes large enough to impact the U.S. economy as a whole.

### **3. Photovoltaic (PV) Power**

Photovoltaic (PV) cell solutions are the most demanding in terms of resources as compared to all of the solar energy components. Even the 9% allotted to PV is comparable to the larger CSP power requirement in terms of land requirement. This is also true in the case of glass despite the thinner glass plating. Fortunately, most of these demands are within the U.S. domestic capabilities for production for both glass and silicon, even for the most demanding scenario.

Table 9. Photovoltaic (PV) cell requirements to meet 9% of the reduction goals – power production requirements only

Goal	PV Production (Quad Btu)	Panel Area (Sq Mile) <sup>127</sup>	# 5kW Home* Systems (EA)	3mm Glass Required (tons) <sup>128</sup>	0.2 mm Silicon Required (tons)	Required By
<b>Proportion</b>	9%					
<b>Adjusted EROI</b>	8.20					
<b>Existing Annual U.S. Production</b>	0.015			20,000,000 <sup>129</sup>	276,000 <sup>130</sup>	
<b>Energy Independence</b>	1.0	90.1	4,000	900,000	20,000	2030
<b>Emission Upper**</b>	1.8	161.5	7,200	1,600,000	30,000	2030
<b>Emissions Lower</b>	3.7	339.9	15,100	3,300,000	70,000	2022
<b>Addition for Hydrogen Upper</b>	0.2	17.0	800	200,000	-	2030
<b>Additional for Hydrogen Lower</b>	0.7	59.5	2,600	600,000	10,000	2022
<b>Total Emissions Upper</b>	2.0	178.5	7,900	1,700,000	40,000	2030
<b>Total Emissions Lower</b>	4.4	399.4	17,800	3,900,000	80,000	2022
<b># Single Unit Homes in U.S.: 87,541,000<sup>131</sup></b>						
*Use Existing MWe/Quad Btu Ratio: 20,328						
Solar PV GHG Emissions = 4% of fossil fuel emissions so a slight penalty is applied: 1.04						

Because of the smaller scale of PV deployment, costs are comparatively low when viewed in total. The 5kW building system currently on the market sells for around \$36,000.<sup>132</sup> Buying between 4 and 18 million of these kits will cost between \$140 and 650 Billion. The question is, who pays for these systems? It may not be reasonable to expect 20 million private citizens to spend \$36K on their own, even with a \$5K subsidy.

<sup>127</sup> Land requirements computed as characterized by: Denholm and Margolis, *The Regional Per-Capita Solar Electric Footprint for the United States*.

<sup>128</sup> Using Sanyo 5kW system as model with 25 200 W panels to estimate both glass and silicon requirements. System represents a traditional PV system already on the market, Alter Systems and Sanyo Solar, "Sanyo 200 Watt HIT Solar Panel," Alter Systems, <http://www.altersystems.com/> (accessed October 21, 2008).

<sup>129</sup> Energy Information Agency (EIA), *Economic Profile and Trends: Glass Industry Analysis Brief*.

<sup>130</sup> United States Geological Survey (USGS), *Commodity Statistics and Information*.

<sup>131</sup> U.S. Department of Housing and Urban Development, *American Housing Survey for the United States: 2007* (Washington D.C.: U.S. Department of Housing, U.S. Department of Commerce, 2008), <http://www.census.gov/prod/2008pubs/h150-07.pdf> (accessed October 22, 2008).

<sup>132</sup> Alter Systems and Sanyo Solar, *Sanyo 200 Watt HIT Solar Panel*.

If the government funds these installations completely, how will it oversee their maintenance, prevent neglect, or ensure the systems are not abused or sold? One advantage is lower demand on the power grid system, when compared to the significant changes required by the CSP and wind options.

In summary, the solar future, as required by the goals set forth in this study, represents a substantial departure from today's energy system. The power grid of today, fed by over 9,000 plants of various shapes and sizes, will be replaced by a massive concentration of power capacity in the southwestern desert, thousands of wind turbines, and PV systems to be mounted on millions of buildings across the nation. The power grid will require significant investment to realign to new concentrations of power production. A storage capacity will be required to handle the energy requirements when solar energy is unavailable, and some plant capacity will likely be required to provide a baseline power platform immune from solar and wind interruption.

From the least to the most ambition goals, the U.S. economy would need to support between \$700-3,000 Billion in capital costs between now and 2030 (applying a 10% cost to CSP and wind costs for grid adjustments). This investment represents between 0.3-1.5% of the U.S. Real GDP without accounting for the cost of operation and maintenance, land acquisition, and energy storage systems. Does this investment mean these options are not feasible? There are a few reasons to suggest this may not be enough of a barrier to dismiss a solar future as a possibility. First, as mentioned before, the investment of 1% of a nation's GDP is comparable to the cost of the present wars in Iraq and Afghanistan.<sup>133</sup> Some would say that these are wars the U.S. cannot afford due to current economic challenges facing the country. However, it may still be safe to claim that if the U.S. can afford a war, it can afford alternative energy. Solar pessimists when examining cost figures frequently forget that these investments yield significant benefits which may outweigh the costs. As the industry matures, prices will likely go down as providers at all levels become more efficient. There is no telling how many other

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<sup>133</sup> Robert J. Barro, "Why the War Against Terror Will Boost the Economy," *Business Week*, no. 3756 (November 5, 2001), 30, <http://proquest.umi.com/pqdweb?did=87509466&Fmt=7&clientId=65345&RQT=309&VName=PQD>.

benefits will come about as this technology grows. Additionally, there are the costs of not taking action, costs which may dwarf these investment figures especially if climate change predictions come to pass. Finally, remember that the goal for energy independence is to reduce the costs of oil dependence to below 1% of GDP. Once solar energy is deployed as recommended here, the U.S. will no longer be paying this premium for energy.

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## **IV. RESOURCE ACCESS**

### **A. THE ACCESS QUESTION**

Solar and nuclear energy each come with a unique stratum of resource demands. The security problems associated with these demands have to do with the availability of resources to meet this demand, how these resources are controlled, and which countries exercise this control. This dialogue will chiefly center on the most demanding goal for these options, that is the energy shift required to support a GHG reduction goal based on U.S. share of population. The following paragraphs will focus on answering the questions: will the shift toward nuclear or solar energy resolve the dilemmas of the status quo; or will problems persist changing nothing more than the resource? The potential crisis with fossil-fuel-based energy include three general concerns. First, market consolidation within the oil market conveys disproportionate power to nations whose interests may conflict with those of the United States and its closest allies, all of which are major net importers of petroleum. Second, control over energy resources by governments known for corrupt or arbitrary behavior may lead to at best an unpredictable energy market, or at worst, a market driven by state actors that use their reserves to manipulate the energy market for political gain. Finally, the fossil-fuel industry drives a need to engage with governments abroad to secure energy resources, creating an economic dependency on other governments in competition with other fossil-fuel-consuming nations, a recipe for conflict. Ideally, the resource demands of a new energy system will involve a non-consolidated market, free from monopolistic or oligopolistic control. Resources should be available from nations with stable governments. Finally, the best solution will not require Carter-Doctrine-like protection abroad thus freeing the United States from complicated security arrangements with questionable allies and relieving the competitive struggle with other energy-consuming nations.

## **B. SOLAR RESOURCES**

Chapter III provided a scenario for resource demands to support the energy policy shifts required for each energy goal. Resources to make these changes involve land, glass, silicon, and various construction materials, as well as a massive amount of funding (over \$3 Trillion for the most ambitious goal). Although other resources, such as rare metals for PV cells, may cause a future resource concern (depending on the technology that wins out) none of these problems resemble oil as a limited resource.

### **1. Solar Land**

Of all of the resources required for solar power, land is perhaps the one in shortest supply. To make the solar strategy work for the most aggressive goal, CSP will require around 2,800 square miles of desert land, wind energy will require over 38,000 square miles in wind-friendly territory along the coasts and throughout the central plains, and PV panels will take up over 400 square miles on the rooftops of over 20,000,000 buildings. Wind commands the greatest claim for land requiring over 1% of the 3.5 million square miles available land in the United States. However, from this 1% one could subtract all offshore turbines, which may provide a significant portion of this requirement. Additionally, the actual infrastructure footprint will be much smaller as most of the land will be required to provide proper spacing between turbines. In the end, the required land is in the United States, and as such, there is little in the way of foreign control over this asset to the degree that foreign interests control oil or other fossil fuels. Therefore the challenge is in economics, not security, when considering access to land.

### **2. Solar Raw Materials**

Solar's need for raw materials is massive in market terms, but there is no question of resource depletion, merely of production capacity. Reserves of silicon, the most challenging resource problem relative to current (very modest) market requirements, are not even estimated.<sup>134</sup> If solar cell technology requires the use of rare earth elements

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<sup>134</sup> United States Geological Survey (USGS), *Commodity Statistics and Information*.

this picture would change, as in the case of thin-film PV technology.<sup>135</sup> Many of these rare elements are extracted as part of the mining operations of other elements such as copper, lead, or zinc.<sup>136</sup> These mining operations can be subject to the same problems with resource nationalism as fossil fuels, though on a smaller scale due to a more diverse network. Battery technology for energy storage will present a similar challenge depending on which battery technology survives the test of time in the hybrid/electric vehicle market.

### **3. Solar Market Consolidation**

The small scale of solar industry makes comparison with fossil fuels or even nuclear energy markets difficult. The numbers of companies involved are few, and predicting vulnerability to monopolistic control as the industry matures requires too much uncertainty to be useful. However, a couple of general points can provide some perspective. The challenges of today are such that analysts measure the health of the industry in terms of the behaviors of individual companies, and their ability to cope with material shortages, market volatility, and changes in production methods. There is no speculation about resource nationalism in relation to silicon, glass, concrete, or steel , as there is for the oil or uranium markets. Consider the PV cell market case. Because materials for both wind and CSP projects are readily available, PV cell production presents the most challenging dilemma with regard to market consolidation. The handful of companies which produce these cells are exhausting the current supply of solar grade silicon, which mostly derives from the high-grade scrap created by integrated circuit production. Silicon providers are accordingly beginning to provide dedicated production to support this market, which has now grown to match the silicon demand of semiconductor manufacturing.<sup>137</sup>

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<sup>135</sup> Jack Lifton, "Thin-Film Solar Cells, Other than those which use A Form of Silicon, are Not Practical due to Natural Resource Limitations," *The Expert Network*, September 17, 2008, <http://www.glgp.com/News/Thin-Film-Solar-Cells-Other-Than-Those-Which-Use-A-Form-of-Silicon-Are-Not-Practical-Due-To-Natural-Resource-Limitati-27898.html> (accessed November 5, 2008).

<sup>136</sup> Jack Lifton, "Solar Energy, the Underground Source," *The Resource Investor* (September 12, 2008, 2008), <http://www.resourceinvestor.com/pebble.asp?relid=46003> (accessed November 5, 2008).

<sup>137</sup> John Carey, "What's Raining on Solar's Parade," *Business Week*, no. 3970 (February 6, 2006), 78.

If there is a market consolidation conversation with regard to PV, it is one about private companies, and not about governments. The production of solar cells is dominated by companies which have the technical ability to manufacture cells. These companies are concentrated within the advanced economies of Europe (26%), the United States (9%) and Japan (47%).<sup>138</sup> Although this concentration may suggest the Japan is in the position to exert OPEC-like power over the system, let's not forget that this discussion is generally about private company participation in a free market.<sup>139</sup> The smaller U.S. market share is due in part to a lack of domestic demand or interest, and not due to the lack of capability or access to resources. The United States can grow an industry to support any market because the required resources are at hand within the country. Japan's prominence in PV production does not provide the same leverage enjoyed by oil producing nations. This is not to say that governments do not play an important role. Government-sponsored research, subsidies, and grants have been an integral part of the growth of solar industry on all fronts. As important as these roles may be, they do not rise to the level of resource nationalism. This dampens the strategic concern with market consolidation in the PV case as compared to the status quo, an energy market known to facilitate conflict on a national scale, playing a role in both World Wars.<sup>140</sup>

#### **4. Solar State Control**

Because the markets involved with solar energy are either more diverse or much smaller than the case with fossil fuels, state manipulation within solar markets does not represent the same challenge. Even in the more restrictive PV industry, no state can control the raw material because silicon is everywhere. Chapter II's table examining the governance of countries which control the fossil fuel industry would need to be expanded

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<sup>138</sup> Arnulf Jäger-Waldau, *PV Status Report 2006: Research, Solar Cell Production, and Market Implementation of Photovoltaics* (Ispra, Italy: European Commission DG Joint Research Centre, 2006).

<sup>139</sup> Ibid.

<sup>140</sup> Daniel Moran, "The Battlefield and the Marketplace: Two Cautionary Tales" In *Energy Security and Global Politics: The Militarization of Resource Management*, eds. Daniel Moran and James A. Russell (London; New York: Rutledge, 2009), 19-38.

to include all nations. At any rate, in the PV case the countries which do enjoy large market share, such as the United States, Japan, or Europe, would score comparatively well using the governance measures in Chapter II.

### **5. Solar Security Abroad**

Because the United States has access to nearly all of the components to produce solar power, there is no need for a Carter-Doctrine-like security arrangement to safeguard energy resources. Although this picture may change for rare-earth requirements, the diversity of solar technology options would diminish this effect.

In summary, there is some uncertainty as to solar resources, but there is also no clear-cut reserve depletion problem resembling the fossil fuel challenge of the present. As such, solar energy offers an improvement to the U.S. security posture as compared to the status quo. Because of the varied methods of production and the availability of most of the resources from domestic sources, the United States may be able to reduce its protective footprint abroad and concentrate on other security challenges.

## **C. NUCLEAR RESOURCES**

The nuclear resource question is more directly comparable to the fossil fuel case due to the finite nature of nuclear resources and the control of these resources, and specifically uranium, by a few key states.

### **1. Uranium**

Uranium is the primary fuel for nuclear power as provided by nature. Natural uranium typically contains two main isotopes:  $^{235}\text{U}$  (0.7%, by mass) and  $^{238}\text{U}$  (99.3%).<sup>141</sup> Because most traditional reactors use  $^{235}\text{U}$  as the primary fissile nucleotide, there is a need to enrich the concentration of  $^{235}\text{U}$  above what is typically mined, typically to between two and four percent.<sup>142</sup> Most reactors (including all those in the U.S.)

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<sup>141</sup> Bodansky, *Nuclear Energy: Principles, Practices, and Prospects*, 199.

<sup>142</sup> Ibid., 199.

utilize  $^{235}\text{U}$  “once-through” fuel cycle, where  $^{235}\text{U}$  is used as a fuel, and all remaining post-reaction materials are treated as waste.<sup>143</sup> As indicated in Chapter III, any move toward nuclear energy to the degree required by the more demanding goals in this study would require a departure from this fuel cycle. Of these many methods of recycling or producing nuclear fuel, the most promising involve the use of breeder reactors. This is the technology which provides the improvement of fuel consumption by a factor of fifty as discussed in the previous chapters. This is achieved in a fast breeder reactor (FBR) by using both plutonium ( $^{239}\text{Pu}$ , produced in another uranium reactor) and  $^{238}\text{U}$  to provide power while breeding more  $^{239}\text{Pu}$  to sustain the reaction (more  $^{239}\text{Pu}$  is generated than initially consumed).<sup>144</sup> Whatever the method, one can safely assume that the management of uranium will remain a strategic challenge until demand is such that control of uranium reserves is of little concern.

## **2. Nuclear Market Consolidation**

Today’s mix of reactors demand more uranium than the FBR mix required by this push toward nuclear energy. As such, analysts should address the uranium market as a highly competitive strategic concern, at least until FBR technology reduces demand such that domestic reserves could last for the foreseeable future. Therefore, security strategists must handle the question of who controls the reserves of uranium, just as they must consider who controls oil reserves.

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<sup>143</sup> Bodansky, *Nuclear Energy: Principles, Practices, and Prospects*, 194.

<sup>144</sup> Ibid., 188-189.

Table 10. 2007 Uranium Reserves and Production – Top 15

Country	Uranium Reserves <sup>145</sup>			Uranium Production from Mines <sup>146</sup>		
	tons U	Rank	%	tons U	Rank	%
<b>Australia</b>	1,243,000	1	23	8,611	2	21
<b>Kazakhstan</b>	817,000	2	15	6,637	3	16
<b>Russia</b>	546,000	3	10	3,413	4	8
<b>South Africa</b>	435,000	4	8	539	11	1
<b>Canada</b>	423,000	5	8	9,476	1	23
<b>United States</b>	342,000	6	6	1,654	8	4
<b>Brazil</b>	278,000	7	5	299	13	1
<b>Namibia</b>	275,000	8	5	2,879	6	7
<b>Niger</b>	274,000	9	5	3,153	5	8
<b>Ukraine</b>	200,000	10	4	846	9	2
<b>Jordan</b>	112,000	11	2	--	--	--
<b>Uzbekistan</b>	111,000	12	2	2,320	7	6
<b>India</b>	73,000	13	1	270	14	1
<b>China</b>	68,000	14	1	712	10	2
<b>Mongolia</b>	62,000	15	1	--	--	--
<b>Rest of World</b>	210,000		4	470		1
<b>Total</b>	5,469,000.00			41,279		

Table 10 is the uranium counterpart to the oil reserve chart in Chapter II. Although the mix of countries are different, there is some similarity with respect to the disparity in reserves control, and the middle-of-the-pack position of the United States in the rank order of control. There are a couple of potential advantages for the United States with respect to nuclear power. First of all, the U.S. share of the total reserves is larger than in the case of oil by a factor of three. Second, if breeder technology is implemented as proposed in Chapter III (Figure 1) the U.S. reserves may last a very long time. In addition, the uranium market is not as developed as the oil market. Additional discoveries are likely, which might change the structure of this chart considerably.

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<sup>145</sup> Reserves figures from WNA are at an extraction cost of \$130/kg U. World Nuclear Association, *Supply of Uranium*.

<sup>146</sup> World Nuclear Association, "World Uranium Mining," World Nuclear Association, <http://www.world-nuclear.org/info/inf23.html?terms=uranium+production> (accessed September 02, 2008).

To compare the market consolidation in the uranium market to the status quo, Figure 1 provides the same measures as provided in the oil discussion using a rather extreme forecast omitting savings from FBR implementation. This chart assumes a 5% shift in nuclear fuel demand in line with the more aggressive scenarios for nuclear energy without breeder technology.

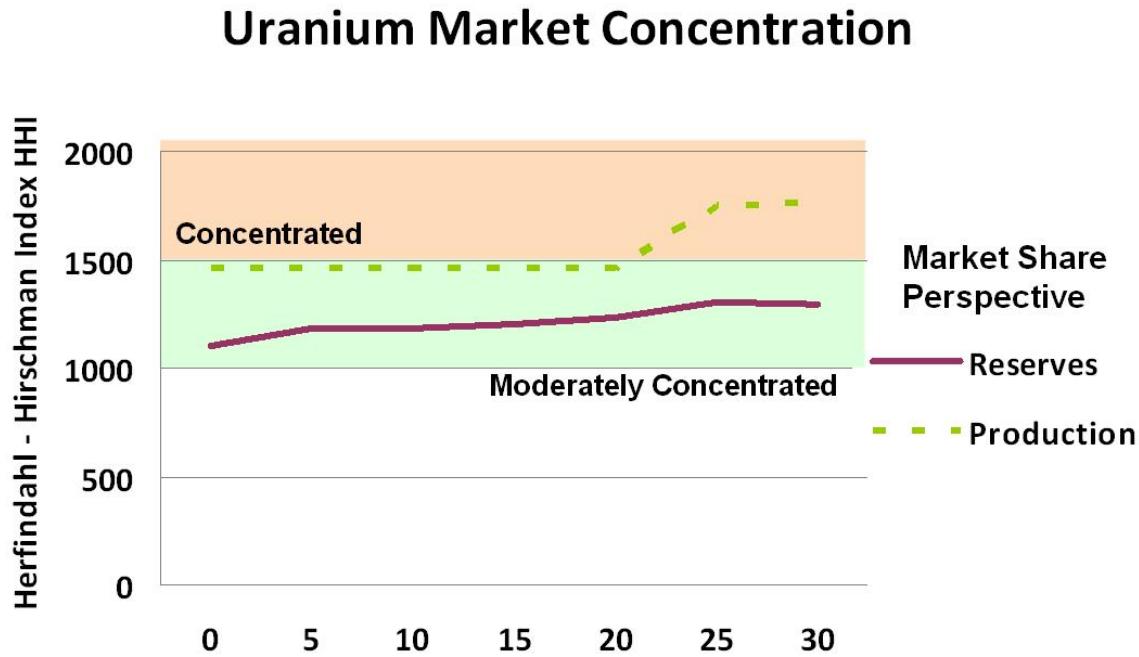


Figure 9. HHI computation for the World Uranium Market. Based on World Nuclear Association 2008 Figures, assuming a 5% increase in annual demand with NO BREEDER REACTORS. All countries are treated as independent actors.

At first glance one could conclude that the similarity between Figure 9 and the same graph for oil would indicate that both options suffer the same vulnerability. Before drawing such conclusions, one should consider that limitations of this prediction are the same as those listed in Chapter II for the oil diagram. The chart also neglects the influence of FBR implementation, a required feature for the shift to take place to achieve the study goals. With breeder reactors, demand would go down, and the upward trends in this chart would stay level, a position which would indicate a “Moderately Concentrated” market. However, even this characterization would overstate the effect of consolidation.

If demand is reduced to a negligible level as compared to reserves, the U.S. market need only consider outside sources if they can provide nuclear fuel cheaper than it can provide for itself domestically. It becomes an economic concern, beneath the level of national strategy as long as the effects are strictly market driven.

### **3. Nuclear State Control**

Despite the reduced concern with state control, Table 2 provides a comparison of the different nations economic and governance indicators to echo the similar table provided in the oil case.

### Top 15 Uranium Reserve Countries, National Index Statistics

Country	2007 GDP (\$ Billion) <sup>147</sup>	Unempl 148	GDP/cap (Intl \$ PPP) <sup>149</sup>	Corruption Perceptions Index <sup>150</sup>	Human Development Index <sup>151</sup>	Freedom House Ratings <sup>152</sup>	Civil Libertie s
<b>Australia</b>	909	13%	43,163	8.7	<b>0.96</b>	<b>1</b>	<b>1</b>
<b>Kazakhstan</b>	105	7%	10,837	2.6	0.79	no data	no data
<b>Russia</b>	1,290	6%	14,704	2.5	0.80	6	5
<b>South Africa</b>	283	24%	9,767	4.9	0.67	2	2
<b>Canada</b>	1,436	6%	38,614	<b>8.5</b>	<b>0.96</b>	<b>1</b>	<b>1</b>
<b>United States</b>	<b>13,807</b>	5%	<b>45,725</b>	7.3	0.95	<b>1</b>	<b>1</b>
<b>Brazil</b>	1,314	9%	9,703	3.5	0.80	2	2
<b>Namibia</b>	7	5%	5,250	4.5	0.65	2	2
<b>Niger</b>	4	no data	667	2.8	0.37	3	4
<b>Ukraine</b>	142	7%	6,968	2.5	0.79	3	2
<b>Jordan</b>	16	13.5%	4,906	5.1	0.77	5	4
<b>Uzbekistan</b>	22	<b>0.8%</b>	2,389	<b>1.8</b>	0.70	<b>7</b>	<b>7</b>
<b>India</b>	1,100	<b>25%</b>	2,563	3.4	0.62	2	3
<b>China</b>	3,308	4%	5,325	3.3	0.78	7	6
<b>Mongolia</b>	4	4%	3,222	3.0	0.70	2	2
<b>Most Favorable Score</b>				10	1	1	1
<b>Least Favorable Score</b>				0	0	7	7

As might be expected, there are similarities with the oil reserve measurement. Six countries are on both lists, and the ratings include both favorable and unfavorable scores both in terms of economy and governance. However, the scores are generally more favorable than in the oil case. Of the four index scores, the favorable scores are roughly

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<sup>147</sup> Data from country profiles compiled from International Monetary fund data for 2007. International Monetary Fund, *World Economic Outlook Database, October 2008*.

<sup>148</sup> Data from CIA fact book. Differing fiscal years for some countries was used when consistent information was not available. Central Intelligence Agency, *The World Factbook*.

<sup>149</sup> Data from country profiles compiled from the International Monetary Fund data for 2007. Values in Current International Dollars. International Monetary Fund, *World Economic Outlook Database, October 2008*.

<sup>150</sup> Transparency International, *CPI Table*.

<sup>151</sup> United Nations Development Programme, "United Nations Human Development Report," Palgrave Macmillan, <http://hdr.undp.org/en/statistics/> (accessed March 25, 2008).

<sup>152</sup> Freedom House, *Map of Freedom in the World*.

equal in number to the negative ones. Even discounting the HDI rating which includes GDP, the good scores outnumber the poor ones, a marked improvement over the situation with fossil fuels.

#### **4. Nuclear Security Abroad**

If breeder technology is employed to reduce uranium demand the change to nuclear should diminish the need for taxing security arrangements abroad. As mentioned, the United States has three times the reserve share as in the oil case, and demand can be significantly reduced using the necessary breeder reactors. This is not to say that there will be no requirement for market protection, merely that this need will more directly compare to the generalized protection the United States provides for other commercial markets, which do not carry the strategic value of the fossil fuel trade. On the other hand, uranium presents a more focused security target than in the solar case, which requires a much more diverse set of resources to function.

Nuclear resource access, although similar to the fossil fuel case, represents a significant improvement over oil in terms of market consolidation, state control, and security overseas. This improvement, however, is tied to a change in the industry to include the use of breeder reactors, a move with a different set of security implications with regard to nuclear weapons proliferation covered in the next chapter.

#### **D. SUMMARY**

Both solar and nuclear shifts provide a noteworthy improvement to the security position of the United States as compared to the fossil fuel energy industry. Solar benefits from a broad range of relatively accessible resources not vulnerable to state manipulation or control. The uranium market is more advantageous for the United States because of reduced demand, greater U.S. share of reserves, and an improvement in governance scores for states which possess the larger shares of uranium reserves. However, both improvements are conditional. The solar energy market should restrict reliance on rare earth elements, preventing the management of such resources to become strategic in nature. Without breeder technology, or similar fuel production or recycling

technique, the uranium reserve problem may match the concern with fossil fuels in time. Accepting the conditions which lead to these security improvements, solar energy is the more attractive option using this criteria, because of the diversity of resources outside strict state control and easier access.

## **V. NUCLEAR WEAPONS PROLIFERATION**

### **A. NUCLEAR WEAPON QUESTION**

The impact of nuclear weapons proliferation varies with the different nuclear futures proposed in this study. As might be expected, the most dramatic scenario involves the massive shift toward nuclear power as in the case of the more aggressive GHG reduction goals. Although, readers may consider the security for the lesser goals a matter of degree in comparison to the extreme cases, accepting that a shift without FBR implementation would effectively dodge a new set of challenges covered below. In any case, the following narrative is chiefly concerned with the more assertive nuclear future, one which requires FBR. The chief security interest is the possibility of nuclear weapons in the hands of terrorists, arguably the most severe homeland security scenario imaginable today. The following account assumes that increased nuclear weapons proliferation would increase the possibility for terrorist access to such weapons, at least indirectly. A significant increase in the size of the nuclear power industry would require an equivalent in growth of the number of personnel, markets, and technology to support it, potentially multiplying avenues of access to nuclear material. In addition, FBR plants generate plutonium suitable for use in a weapon.

### **B. INCENTIVES FOR NUCLEAR WEAPONS**

To envisage how states will decide their nuclear weapons future, one can begin with an examination of pertinent incentives. Mitchell B. Reiss provides a useful list of incentives and disincentives for governments as they consider building nuclear bombs. His work is part of a collaborative effort between the Center for Strategic and International Studies and the Reves Center for International Studies at the College of

William and Mary to address recent changes in nuclear weapons proliferation.<sup>153</sup> These incentive and disincentives are provided in Table 11.

Table 11. Reiss list of state incentives for nuclear weapons programs<sup>154</sup>

Incentive	Disincentive
<ul style="list-style-type: none"> <li>- Intimidate and coerce rivals</li> <li>- Enhanced security vs. rivals</li> <li>- Status and prestige</li> <li>- Domestic politics</li> <li>- Self aggrandizement</li> </ul>	<ul style="list-style-type: none"> <li>- Cost</li> <li>- Technical difficulty</li> <li>- Domestic opposition</li> <li>- Damage to international relations</li> <li>- Alliances</li> <li>- Non-proliferation norms</li> </ul>

Considering the security environment of today and the near future, the experts in the study suggest that there are five factors that can drive a country with no nuclear weapons to reverse course. These factors include:<sup>155</sup>

- U.S. foreign and security policy
- The status of the global non-proliferation movement
- Changes in global or regional security
- Domestic politics
- Availability of technology

How will the shift toward nuclear power change this picture? The nuclear scenarios considered here have inherent features with respect to the technology question that may lead to some useful conclusions with respect to the increased availability of

<sup>153</sup> Mitchell Reiss, "The Nuclear Tipping Point: Prospects for a World of Many Nuclear Weapons States" In *The Nuclear Tipping Point Why States Reconsider their Nuclear Choices*, eds. Kurt M. Campbell, Robert J. Einhorn and Mitchell Reiss (Washington, D.C: Brookings Institution Press, 2004), 12.

<sup>154</sup> Ibid., 12.

<sup>155</sup> Kurt M. Campbell, "Reconsidering a Nuclear Future: Why Countries might Cross Over to the Other Side" In *The Nuclear Tipping Point Why States Reconsider their Nuclear Choices*, eds. Kurt M. Campbell, Robert J. Einhorn and Mitchell Reiss (Washington, D.C: Brookings Institution Press, 2004), 19-28.

technology and how this would change the incentives in terms of cost, technical difficulty, status, non-proliferation regime, and national security.

### C. NUCLEAR POWER PROLIFERATION

A four-fold increase in the size of the nuclear power industry by 2030, as required in the most demanding GHG goal, would represent a substantial expansion of the nuclear workforce, dedicated resources, and a reinvigoration of nuclear-related academic research. More students, more engineers and scientists, and more technicians may yield innovations leading to more efficient plant designs, reasonable standards, and streamlined regulatory processes, all changes driven by the economic necessities of the new power industry structure.

Plutonium is a key component of this discussion, as its production is drastically affected by the nuclear power shift. This change is specific to the civilian nuclear power industry transformation, because the uranium enrichment pathway to nuclear weapons would exist with or without an extraordinary multiplication of civilian nuclear power plants. It is generally understood that all reactors can potentially be used to generate plutonium for nuclear weapons.<sup>156</sup> Fissile plutonium ( $^{239}\text{Pu}$ ) is a byproduct of most nuclear processes, as it is generated any time  $^{238}\text{U}$  absorbs an additional neutron as part of  $^{235}\text{U}$  fission. Use of plutonium in weapons is a matter of removing the other contaminates from the  $^{239}\text{Pu}$  present in the post-reaction waste products, to create an ideal concentration of around 90%  $^{239}\text{Pu}$  (although as little as 70% could possibly be used in a bomb).<sup>157</sup> Frank Barnaby, a long-time nuclear expert with the Oxford Research Group, computed a theoretical measure of plutonium available for weapons programs from civilian nuclear energy production and determined that these programs could potentially provide 265 grams of  $^{239}\text{Pu}$  for each MWe power capacity provided, generating enough material for a 20 kiloton bomb for each 40MWe (the Hiroshima bomb has been estimated

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<sup>156</sup> Frank C. Barnaby, "How States can Go Nuclear," *Annals of the American Academy of Political and Social Science* 430, Nuclear Proliferation: Prospects, Problems, and Proposals (March 1977), 29.

<sup>157</sup> Ibid., 33-35.

at 20 kilotons).<sup>158</sup> This would mean that today there is enough <sup>239</sup>Pu produced to generate over 9,000 such bombs from the world's 360,000 MWe nuclear power capacity tracked as operational in the WNA database.<sup>159</sup> The most extreme nuclear future in this study will provide plutonium for another 40,000 bombs annually, if the world adopts the same increased nuclear energy policy as the United States, even without the increased <sup>239</sup>Pu from FBR plants. On the other hand, this fact alone has not led to a significant increase in the number of countries which possess nuclear weapons programs, presumably because of the other factors and incentives referenced earlier. Historically, nuclear power programs have not been an especially prominent proliferation pathway.

The technical barrier to plutonium bomb production is significant. The reprocessing technology used to generate weapons grade plutonium from spent nuclear fuel is rarely developed independently.<sup>160</sup> However, this barrier has not completely prevented nations from developing a weapons program when motivated to do so. India provides a useful historic example. India's weapons program began with a research heavy-water reactor and the plutonium reprocessing capabilities which followed.<sup>161</sup> Both systems are justifiable for use in civilian power production, but in the India case, they were also used to create a nuclear weapons program in the 1990s.

It is reasonable to suggest that a four-fold increase in the size of the nuclear industry will substantially reduce these technical barriers, both in terms of access to the required expertise as well as cost. The proliferation risk associated with nuclear power plants is commonly diffused by the claim that plutonium recovery is a tedious route toward the development of a nuclear weapon, and that proliferation along the uranium enrichment path would more likely occur, with or without civilian power programs, for sufficiently motivated governments.<sup>162</sup> However, those who make such arguments

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<sup>158</sup> Barnaby, How States can "Go Nuclear," 34.

<sup>159</sup> World Nuclear Association, *Reactor Database*.

<sup>160</sup> Cirincione, Wolfsthal and Rajkumar, *Deadly Arsenals: Nuclear, Biological, and Chemical Threats*, 52.

<sup>161</sup> Ibid., 255.

<sup>162</sup> Cravens, *Power to Save the World: The Truth about Nuclear Energy*, 270-271.

typically do not envision a nuclear industry as large as required in this study, which produces unprecedented amounts of  $^{239}\text{Pu}$  with an unprecedented number of opportunities for such material to slip through the cracks.<sup>163</sup> Today, as much as 1% of these materials goes unaccounted for.<sup>164</sup> Additionally, in a world awash with plutonium production capacity, hiding a nuclear weapons program becomes that much easier for countries without access to domestic uranium reserves. This would allow a country to escape detection until it is too late for the international community to respond. The responsibility of securing uranium and plutonium materials is a necessary feature even for pro-nuclear advocates. Part of this security is in the high cost of secrecy, a cost substantially reduced with widespread access to plutonium. The tasks required to protect uranium and plutonium grow to potentially unmanageable levels under this scenario, even before the FBR feature of this nuclear future is taken into account.

#### **D. FAST BREEDER REACTOR**

A critical component of the highest energy transformation goal is use of FBR plants to support the country's energy demands. As discussed, these reactors extend the life of uranium reserves well into the foreseeable future while generating less waste, even as demand rises to unprecedented levels. Although this would represent a substantial improvement to energy security with respect to access, FBR plants magnify the plutonium problem emphasized in the previous section.

As mentioned, civilian energy programs are not necessarily the most efficient way to produce weapons-grade fissionable material, but it is an option, especially in the case of FBR deployment. The potential role for FBR in a nuclear weapons program was a key factor in the Carter administration's decision to abandon FBR development programs in

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<sup>163</sup> Frank Barnaby, *Secure Energy: Options for a Safer World, Security and Nuclear Power* (Oxford, United Kingdom: Oxford Research Group, 2005), [http://www.oxfordresearchgroup.org.uk/publications/briefing\\_papers/pdf/factsheets1-2.pdf](http://www.oxfordresearchgroup.org.uk/publications/briefing_papers/pdf/factsheets1-2.pdf) (accessed November 16, 2008).

<sup>164</sup> Ibid.

the United States in the late 1970s.<sup>165</sup> FBR adds to the  $^{239}\text{Pu}$  problems in two ways. First, FBR plants produce more nuclear fuel than they consume, compared to traditional reactors which generate waste  $^{239}\text{Pu}$  amounting to around one third the uranium fuel used in the process.<sup>166</sup> However, a three-fold increase in the amount of plutonium within the confines of FBR plants does not necessarily equal a three-fold increase in security requirements because the number of sites requiring this security remains the same. The second problem with FBRs is the weapons-grade quality of the  $^{239}\text{Pu}$  within the breeder blankets, which eliminates the need for continued reprocessing.<sup>167</sup> Thus, FBR deployment may reduce the need for the development of separate reprocessing plant technology.

## E. CONCLUSIONS

Implementation of an energy policy shift of the magnitude required by the energy goals in this study reduces two of the six disincentives to the development of nuclear weapons programs, cost and technical difficulty. For review, the five factors which may trigger a policy reversal toward nuclear weapons development include: U.S. foreign or security policy, status of the non-proliferation movement, regional or global security, domestic politics, and access to technology. When considering these factors, the nuclear future as proposed here would shift the availability of technology in favor of a program. Additionally, the creation of a plutonium fuel cycle with over seven-times the amount of plutonium available for weapons programs would present a new security challenge which increases the likelihood of terrorist access to nuclear material. This may have a profound effect on the non-proliferation regime if it becomes overwhelmed by the need to manage unprecedented levels of nuclear material. Such a course of events would weaken the regime's legitimacy, and proliferation may be perceived as inevitable. Such a perception

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<sup>165</sup> U.S. General Accounting Office, *U.S. Fast Breeder Reactor Program Needs Direction: Report to the Congress* (Washington, D.C: U.S. General Accounting Office, 1980), 5; Marvin Baker Schaffer, "Nuclear Power for Clean, Safe and Secure Energy Independence," *Foresight: The Journal of Futures Studies, Strategic Thinking and Policy* 9, no. 6 (2007), 50.

<sup>166</sup> Barnaby, How States can "Go Nuclear," 33.

<sup>167</sup> Ibid., 25.

would encourage the building of nuclear arsenal. Whether or not a government would choose to make such a move would depend on the other factors, which points to a need for the U.S. to influence those factors to limit proliferation.

As mentioned, there are those who would suggest that uranium presents a more attractive option for a weapons program, and that the changes above would not affect this generalization. As such, one could dismiss the concern and treat the proliferation question as the same for both the solar and nuclear power options. Solar power does not prevent uranium enrichment, but it does not require a massive growth in an industry which would provide the same technologies and expertise as a nuclear weapons program. When considering how little material is required to build a bomb, and the extreme consequences if such a bomb were to fall into the hands of terrorists, even a small increase in the likelihood may prove unacceptable.<sup>168</sup>

The greatest hope in this scenario may come from the new research focus on nuclear technology potentially leading to a search for solutions which could provide for a breeder cycle which does not produce weapons grade material. Advances in detection, control, forensics, and response are all possibilities which may counter the proliferation threat to some extent. However, considering the consequences of failure, reliance on a research promise seems irresponsible.

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<sup>168</sup> Barnaby, *Secure Energy: Options for a Safer World, Security and Nuclear Power*, 6.

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## **VI. INFRASTRUCTURE PROTECTION**

### **A. CRITICAL INFRASTRUCTURE PROTECTION**

The final aspect of security as part of these proposed energy changes is the protection of the infrastructure itself. Each energy future provides different outcomes with respect to network security, hardening requirements, and resilience. What follows is an examination of both the nuclear and solar cases as represented by the potential futures outlined in Chapter III. As with previous discussion, the focus below will address how the infrastructure changes with each option, limiting discussion of broader questions that would apply to any energy future, including the status quo.

Before dividing the analysis into each alternative future, readers should understand the proposed approach to critical infrastructure protection (CIP). First, is an examination of the infrastructure network security. The narrative will apply Ted Lewis' textbook approach to general questions with regard to the power networks required in each case.<sup>169</sup> As mentioned, the characterization of the infrastructure system as a system of nodes and links is the foundation of this analysis, as failures are modeled within different nodes or links to evaluate the systems ability to recover from such attacks or propagate failures to different parts of the network. Nodes in the power grid would include power plants, substations, and end-use facilities such as buildings, industrial complexes or homes. Links would include the 150,000-plus miles of power transmission lines webbed across the nation.

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<sup>169</sup> Ted G. Lewis, *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation* (Hoboken, N.J: Wiley-Interscience, 2006), 249.

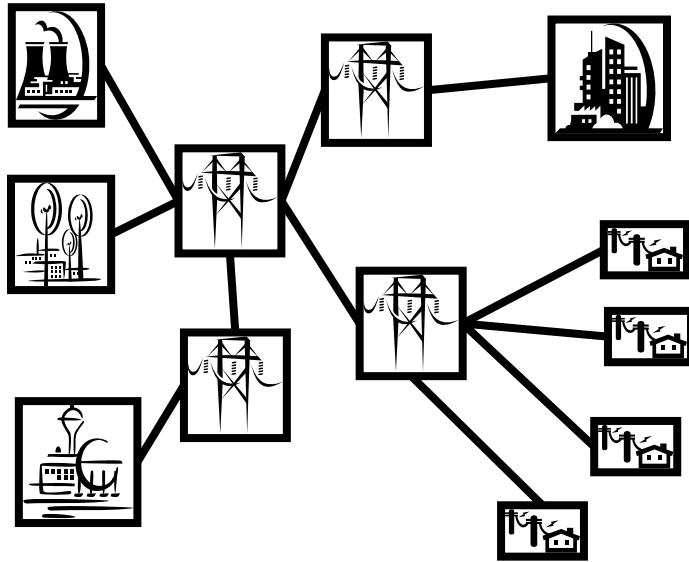


Figure 10. Simple representation of nodes and links in the electrical power infrastructure network.<sup>170</sup>

Lewis' assessment of the electrical power grid includes a few useful observations which can translate to the discussion of both solar and nuclear options. A few relevant observations are quoted as follows:<sup>171</sup>

- a. There is no shortage of power, but there is a shortage of distribution capacity
- b. The “Architecture” of the grid is a *small-world network*-clustered nodes connected to other clustered nodes through a combination of many short and a few long links.
- c. Because of the small-world architecture of the grid, and the laws of physics, the grid is *vulnerable to cascade effects* that can sweep through the power grid interconnects like a contagion sweeps through human populations.
- d. The *greatest vulnerabilities exist “in the middle,”* That is, in the transmission and distribution layer of the power grid.

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<sup>170</sup> An expanded version would show a small world network, clusters of heavy concentrations of links and nodes, with a few longer key links connecting them to key substations or power production facilities.

<sup>171</sup> Ibid., 249-250.

- e. No single power generator is critical-the largest power source provides less than 1% of the national capacity.

These five factors will serve as benchmarks in the following discussion as each energy future affects them in different ways. Will the new energy future improve the security challenges with respect to network structure?

Although plant security is part of the network security question, it does warrant additional consideration beyond network analysis. This has to do with the attractiveness of the plant as a target for terrorist attack, and the capabilities that can be provided to secure these plants. Does the new security solution provide better targets for terrorists? Are these assets protectable?

Finally, there is the matter of network resilience. This involves investigating how the system would recover from failure. As discussed, hardening of the entire system against a vast array of unpredictable threats is probably not affordable, but taking measures to improve network resilience are attractive for both security and economics. For the power grid, resilient strategies have included: building redundant links; proposing a smarter network, more resistant to cascading failures;<sup>172</sup> or bolstering emergency response capabilities.<sup>173</sup> These measures would pay off for any type of failure path, both natural and man-made, contrasting with protective hardening measures such as physical barriers or security forces that chiefly prevent man-made threats. How will the proposed changes in energy policy affect the picture with respect to resilience? Will the new path lead to a fragile or flexible network?

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<sup>172</sup> Massoud Amin, "Toward Self-Healing Infrastructure Systems," *Computer* 33, no. 8 (Aug, 2000), 44, <http://proquest.umi.com/pqdweb?did=58512312&Fmt=7&clientId=65345&RQT=309&VName=PQD>.

<sup>173</sup> Anna K. Schwab, David J. Brower and Katherine Eschelbac, *Hazard Mitigation and Preparedness: Building Resilient Communities* (Hoboken, NJ: J. Wiley, 2007), 568.

## **B. NUCLEAR INFRASTRUCTURE PROTECTION**

As mentioned, the nuclear future will require 100-600 nuclear plants to replace fossil fuel plants within the U.S. inventory of over 9,250 existing non-nuclear power plants for the most part owned and secured by private industry. Although this change does represent some consolidation in terms of production, for the most part, this analysis assumes these changes should pose no new problem for the existing power grid as a whole, beyond local adjustments.

### **1. Network Security**

The nuclear future involves plugging new plants to the power grid and taking a larger number of fossil fuel plants off line. Although this does reduce the number of power producing nodes, the small world character of the middle of the network will remain unaffected. One could create a nuclear version of Figure 10 just by replacing all plant icons with nuclear symbols. This would suggest that Lewis's five network security observations will likely hold true for the nuclear network. This is not to say that the network will behave exactly the same. Lewis' points out that no single power source provides 1% of the energy supply carries more weight with the current system of 9,000 plus plants than a nuclear future with around 600 FBR facilities.

The similarities end when the energy network is extended to consider the supply of fuel to keep the plants running. Today's plants are fed oil and natural gas through a system of pipelines resembling another small world network, and a fed coal through the country's rail and road networks.<sup>174</sup> These networks are generally owned and secured by private industry. Although the pipeline systems are seen as potential targets, the system has yet to be subject to attack in the United States. The American Petroleum Institute, in conjunction with the Department of Homeland Security (DHS), has developed security guidelines with a focus on intelligence, planning, communications,

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<sup>174</sup> Lewis, *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation*, 292.

and risk assessment.<sup>175</sup> There is no wide-spread effort to secure these assets by the federal government. Although, there are rigid regulatory requirements for the transport of nuclear material, the security of materials in transit remains in the hands of private entities.<sup>176</sup> Although the implementation of the proposed nuclear future would vastly increase the number of plants as part of the most extreme shifts, the use of FBR plants will represent a net decrease in demand for raw nuclear material. This reduction diminishes the need for security for the transport of nuclear fuel, private or otherwise. This assumes that each FBR operates in a closed cycle each producing its own fuel. If these reactors are used to produce plutonium for other reactors, the transport of that fuel will add to the transport security burden. At any rate, the challenge posed by the transportation of nuclear fuel by the changed nuclear future would resemble that of today, all else being equal, varying only in magnitude of regulatory action. Thus the primary network security concern in the nuclear case is for the plants themselves.

## 2. Plant Security

The need for plant security represents the greatest change in security requirements posed by the nuclear course. Since 9-11, the possibility of a terrorist attack on a nuclear plant has captured the attention of national leadership.<sup>177</sup> Nuclear plants have long been attractive targets for terrorists and were even part of the original 9-11 target considerations.<sup>178</sup> The defense of that nation's 104 nuclear power plants employs over 5,000 private security personnel trained to handle attacks in accordance with the Design

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<sup>175</sup> American Petroleum Institute, Security Guidelines for the Petroleum Industry, 3rd ed. (Washington, DC: American Petroleum Institute, 2005), 58.

<sup>176</sup> U.S. Department of Transportation, Research and Special Programs Administration, 49 CFR Part 172 Hazardous Materials: Security Requirements for Offerors and Transporters of Hazardous Materials, Vol. 68 (Washington D.C.: Department of Transportation, 2003), 14521; U.S. Nuclear Regulatory Commission, "NRC Regulatory Guides - Transportation (Division 7)," U.S. Nuclear Regulatory Commission, <http://www.nrc.gov/reading-rm/doc-collections/reg-guides/transportation/active/> (accessed 11/21, 2008).

<sup>177</sup> Mark Holt and Anthony Andrews, Nuclear Power Plant Security and Vulnerabilities (Washington, D.C.: Congressional Research Service, Library of Congress, 2008), 2.

<sup>178</sup> National Commission on Terrorist Attacks upon the United States, *The 9/11 Commission Report: Final Report of the National Commission on Terrorist Attacks upon the United States*, 1st ed. (New York: Norton, 2004), 245.

Basis Threat (DBT), a collection of classified threat scenarios developed by the Nuclear Regulatory Commission (NRC).<sup>179</sup> The DBT document provides threats for which security systems should be designed to resist. This design would include the engineering of the plant itself and the management of the security force. Even as the DBT has been expanded to include greater threats, the DBT has been a source of debate between protection advocates and the nuclear energy industry. Many advocate that the DBT should be increased to include more demanding threat scenarios, such as an aircraft attack or a larger ground attack with greater explosive capabilities. The industry contends that the security against an air attack is already accounted for by other security measures often provided by the U.S. government.<sup>180</sup> The U.S. Government Accounting Office (GAO) took the NRC to task for adjusting the DBT in response to industry complaints that certain threat weapons systems or modes of attack in the DBT were not affordable to defend against.<sup>181</sup> This balancing act suggests that even the roles and responsibilities of nuclear plant security are not resolved.

One could reasonably expect that any increase in threat toward nuclear facilities would drive an increase in federal involvement in plant security. The price of failure is too high. Even if NRC manages to push the bill to the private companies, the price falls on the U.S. public to fund. Since nuclear power plant already have the most rigid security standards, any increase in nuclear plant capacity would represent a marked increase in security requirements in terms of investment, manpower, and regulatory effort.

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<sup>179</sup> Holt and Andrews, *Nuclear Power Plant Security and Vulnerabilities*, 2.

<sup>180</sup> United States. Government Accountability Office, *Nuclear Power Plants Efforts made to Upgrade Security, but the Nuclear Regulatory Commission's Design Basis Threat Process should be Improved* (Washington, D.C.: U.S. Govt. Accountability Office, 2006), 6; Holt and Andrews, *Nuclear Power Plant Security and Vulnerabilities*, 3.

<sup>181</sup> United States. Government Accountability Office, *Nuclear Power Plants Efforts made to Upgrade Security, but the Nuclear Regulatory Commission's Design Basis Threat Process should be Improved*, 6-7.

### **3. Resilience**

Transition to a nuclear power industry could improve energy resilience, but only by virtue of new construction, standard designs, and updates to response plans. Building new energy infrastructure provides an opportunity to incorporate common designs, build in smarter monitoring and control systems, improve communications networks, develop common data protocols, and any number of improvements which might go along with a nation-wide mobilization of a power industry fueled by a trillion-dollar investment. That said, none of these improvements are necessarily nuclear specific. The nation might build a new fossil fuel system and realize the same benefits. Because an update to the plant capacity does not necessitate improvements to the power grid itself, the primary weaknesses in the system would go unaddressed. All of the problems with fault propagation, lack of redundancy, and tapped capacity would persist. One key nuclear-specific-benefit is the lower critical resource demand of FBR plants. Because the demand for uranium is low, plants are less vulnerable to interruptions in raw material acquisition and transport systems, and could function independently with a smaller inventory of reserve uranium stock.

## **C. SOLAR INFRASTRUCTURE PROTECTION**

The solar case as provided in Chapter III does present a future markedly different from the status quo on all fronts. The following breakdown takes the general structure of the suggested CSP, wind, and PV cell power network and reviews its network security, plant protection, and system resilience.

### **1. Network Security**

The solar prospect as outlined in this study presents a new type of power network. The change does not necessarily affect the small-word characterization of the power grid, but does affect the nature of power production within that network. In some cases, the solar future represents a massive consolidation of power production, especially in the case of CSP. In the most extreme case, CSP would provide nearly one third of the nation's power from 2-3 thousand square miles of the south western desert. This would

change Lewis' observation that no plant will provide more than 1% of the country's electrical energy. Wind power would probably promote some concentration as well. Take the most extreme case where hundreds of thousands of wind turbines are put into place. On the surface, this may look like an increase in distributed power, but remember that these turbines will likely be deployed thousands at a time in land areas restricted to certain regions of the country or off-shore. This, combined with the CSP consolidation, would remake the grid to include more long-distance, critical links as part of grid's weak middle. A few adjustments to the solar scenario could address this problem. First, the CSP consolidation could be used for hydrogen production to provide fuel for the transportation sector, 25% of the primary power demand. Such a move would reduce demand on the grid and the criticality of the links to the southwestern desert. Of course, hydrogen may not be the final solution for the transportation sector, and if not, these benefits may not come to fruition. Another adjustment would entail an reduction in CSP capacity, increasing wind or PV to make up the difference. Such a move may prove necessary, but at the expense of the efficiency gains with respect to EROI, which motivated the CSP consolidation in the first place. Additionally, since these adjustments to the grid may involve the construction of new transmission lines there is the possibility that the new systems may benefit from new engineering advances. Thus the few new strong links may be more secure than the many old links they are replacing. One the other hand, there is generally no security for the thousands of miles of transmission lines. A determined enemy will find a way to break a critical link in a remote location (like the desert), no matter how well engineered the lines are. Even if redundancies are provided, it is possible that there will be a reduction in the effort required for terrorists to disrupt a substantial portion of the network if there are fewer critical links.

The greatest counter to the power consolidation problem is the combination of the third component to the solar future, photovoltaic (PV) cell capacity and energy storage. PV power capacity distributed to millions of facilities across the country would diminish the impact of any critical link breakage.

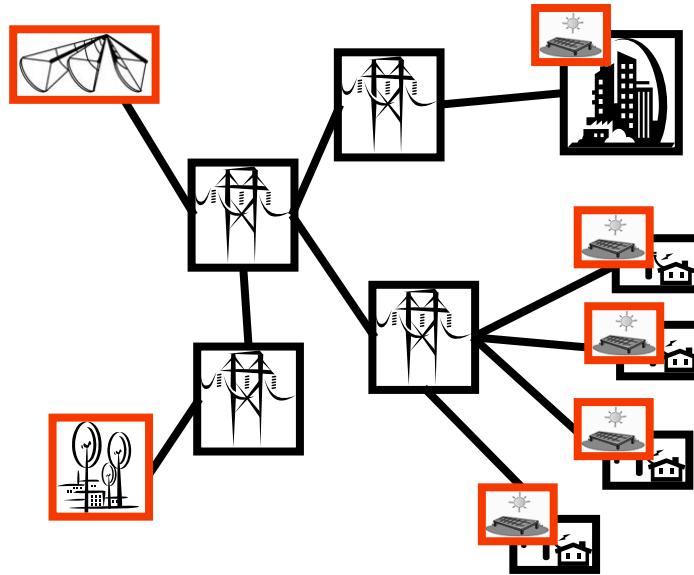


Figure 11. Simple representation of nodes and links in the solar electrical power infrastructure network. CSP and Wind Energy feed the grid from the left, and PV power sources are dispersed throughout the system, often collocated with final customers.

The presence of PV power sources throughout the power consumer base would detract from the impacts of any power grid breaks. PV dissemination would also reduce the attractiveness of the grid as a target for terrorists. Even though many would be without power, a large number would have enough power to support critical activities. If the required energy storage capacity is provided, such a capability would provide a temporary source of power while grid repairs are completed. These changes would make it difficult for terrorists to assess the impacts of an attack to the grid.

Unlike the nuclear question, expansion of the solar network to include the supply networks for raw materials does not involve new security problems that differ substantially from the status quo. Silicon, glass, concrete, steel, or other solar components have not captured the attention of strategy analysts as has fossil fuel supply or uranium. Because the solar shift will relax demand for fossil fuels, one could reasonably suggest that such a change would relax anxiety over fossil fuel infrastructure security. This fact may prove a net gain in security for the solar network.

## **2. Plant Security**

Solar plants do not pose an interesting security problem as compared to the nuclear plant challenge. Simply put, attacking a collection of wind turbines or a farm of CSP mirrors would involve a fairly tedious effort, without the drama of a nuclear panic. The destruction of the solar panels on a building will hardly make the front page. The only concentration of plant capacity providing an interesting target would be the CSP plants in the desert. These remote locations will benefit from a healthy standoff distance and a reduced local population within which a terrorist cell could operate. For this reason, the bulk of the security problems are in the grid as already discussed.

## **3. Resilience**

Since the chief concern with the solar future is the status of the grid, the resilience of this new grid is of primary importance, because as mentioned, the complete protection of this vast system is probably not feasible, even with fewer critical links. As in the nuclear case, the solar future will involve a great deal of new designs, new construction, and increased professional focus, which should all contribute to improved system resilience. This effect may weigh heavier in the solar case, because of the increased grid construction required. Of course this is a fairly obvious point. Improvement through investment in new construction is a benefit that any energy future could realize once the funds become available. Thus, the solar future security is enhanced in part because it costs more. However, there are features which do enhance resilience in the system, that are unique to the solar future. The previously made point about the effectiveness of an attack on the solar power infrastructure hold true mostly because of the resilience provided by the PV distributed power capacity and from the required energy storage means. The storage capacity benefit, although mandated by solar energy, is a purchase that could be made for any energy future, but few would expect such an investment without the emphasis solar brings.

If there is a weak point in solar resilience, it comes from the addition of a new vulnerability, the weather. Imagine a third of the nation's energy supply affected by cloud cover in the desert or a change in wind patterns. Naturally, this could be balanced

by other energy sources or the energy storage inventory. How this would effect the system is difficult to surmise without delving into the engineering questions which surround each energy or storage choice available in the solar vision. Unfortunately, like many of the solar energy questions, unless this study moves even more into the realm of unproven solutions, readers must settle for the answer: the engineers will solve this problem because they have to. Nonetheless, because this new vulnerability is solar-specific, it warrant some consideration.

#### **D. SUMMARY**

Between the solar and nuclear futures as represented in Chapter III, solar appears to offer the greatest improvement over the status quo. Nuclear power provides a more attractive target set for terrorists and requires more physical security. Each future does provide some improvements above the status quo and some concerns. Power production concentration within the small-world power grid may provide attractive links for terrorist attack. A necessity for all of the future options is a mammoth investment, providing an obvious conduit for improvement for both security and resiliency. The most compelling departure from the status quo is the proposed distributed power capacity provided in the solar fortune, dampening the effects of any network failure, and reducing the attractiveness of the national power infrastructure as a target for attack.

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## VII. CONCLUSIONS

Many predict that the world is destined to create a “post-petroleum age” the international community grapples with many dramatic changes in the next 20 years, from climate change and economic restructuring to nuclear weapons proliferation and strategic power rebalancing.<sup>182</sup> The United States must build an energy future that can improve its security posture, while relieving the economic and environmental burdens of the status quo. This thesis began with a measurement of these burdens in terms of potential oil shortage, energy independence, and climate change, and crafted goals for each challenge. These goals were next applied to two alternative energy futures, solar and nuclear energy, to determine what systems were required to meet the different goals. Although these predictions were, for the most part, an extension of existing solutions with some history of performance, there is still a great deal of uncertainty in these forecasts. Many problems have yet to be solved.

As expected, these future prospects involve a massive mobilization of resources. The most demanding climate change goal requires a complete makeover of the energy industry, requiring a nearly complete replacement of fossil fuel systems by 2022. As such, these goals push the U.S. energy infrastructure to incorporate hundreds of FBR nuclear plants or to construct an unprecedented solar infrastructure involving thousands of square miles of desert CSP plants, hundreds of thousands of wind turbines, millions of smaller PV systems installed on rooftops across the country, a drastically modified power grid, and an energy storage solution to manage fluctuations in solar energy supply.

On the whole, both solar and nuclear futures represent improvements to security as compared to the fossil fuel industry. Nuclear weapons proliferation being the most notable exception to this trend. Table 12 summarizes the general findings for each criteria.

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<sup>182</sup> National Intelligence Council, "Global Trends 2025 a Transformed World," National Intelligence Council, [http://www.dni.gov/nic/PDF\\_2025/2025\\_Global\\_Trends\\_Final\\_Report.pdf](http://www.dni.gov/nic/PDF_2025/2025_Global_Trends_Final_Report.pdf). (accessed November 24, 2008).

Table 12. Solar versus Nuclear - Security Criteria Summary

Nuclear America	Solar America
Resource Access	
<b>Pros:</b> <ul style="list-style-type: none"> <li>- Greater U.S. control over reserves</li> <li>- FBR possibility for vastly reduced demand</li> <li>- Lower demand dampens drive toward resource nationalism and monopolistic/cartel control</li> <li>- Improved record of governance for countries that control uranium as compared to oil</li> </ul> <b>Cons:</b> <ul style="list-style-type: none"> <li>- Uranium is an essential and limited resource</li> <li>- FBR solutions required to avoid eventual resource shortages</li> </ul>	<b>Pros:</b> <ul style="list-style-type: none"> <li>- The required variety of raw materials are readily available on the open market</li> <li>- No singular resource dependency vulnerable to resource nationalism</li> <li>- Many components are recyclable</li> </ul> <b>Cons:</b> <ul style="list-style-type: none"> <li>- Significant demand for construction material and funding</li> <li>- Potential for rare-earth material requirements for PV and energy storage solutions</li> </ul>
Nuclear Weapons Proliferation	
<b>Pros:</b> <ul style="list-style-type: none"> <li>- Influx of research focus may yield breeder cycles without weapons grade material, or improve nuclear detection, defenses, forensics, or response</li> </ul> <b>Cons:</b> <ul style="list-style-type: none"> <li>- Significant increase in the size of the nuclear industry vastly multiplies the security challenges with regard to nuclear technology, personnel, and weapons grade plutonium</li> <li>- Proliferation may seem inevitable, eroding the legitimacy of the non-proliferation regime</li> <li>- Disincentives for the development of a weapons program are diminished in terms of both cost and technical difficulty</li> </ul>	<b>Pros:</b> <ul style="list-style-type: none"> <li>- Unrelated to weapons proliferation</li> </ul>
Infrastructure Protection	
<b>Pros:</b> <ul style="list-style-type: none"> <li>- New plant construction offers opportunity to upgrade security designs, communications and monitoring systems, and response plans</li> <li>- FBR plants less vulnerable to resource supply interruption</li> </ul> <b>Cons:</b> <ul style="list-style-type: none"> <li>- Nuclear plants are attractive targets for terrorism</li> <li>- Nuclear industry requires the most demanding plant security and the most rigid regulatory requirements</li> <li>- Does not address the vulnerabilities in the middle of the small-world network</li> </ul>	<b>Pros:</b> <ul style="list-style-type: none"> <li>- Resilience benefits from massive new construction effort for both plants and grid</li> <li>- Distributed PV power sources and required power storage solutions would reduce the impact of any power interruption</li> <li>- Plants are not interesting targets for attack</li> </ul> <b>Cons:</b> <ul style="list-style-type: none"> <li>- Concentration of power capacity in the desert may provide critical links vulnerable to attack</li> <li>- Does not address the vulnerabilities in the middle of the small-world network</li> </ul>

As Table 12 illustrates, from a security perspective, solar would be the alternative of choice. Nuclear power requires more security, carries the possibility for weapons proliferation, and involves potentially catastrophic consequences for security failure. These conclusions assume that solar power gets a pass on a few technical hurdles which may complicate the execution of the proposed outcomes, funding, storage solutions, and economy of scale to name a few. If, for example, solar power cannot deliver on its promises, the question becomes, is nuclear power an improvement over the status quo? Policymakers must strike a balance between the need for a secure energy source and potential nuclear weapons proliferation.

There is the possibility that the United States will reject the notion that it must choose between these possibilities. Civilization's addiction to energy grows with its supply. Is it reasonable to expect the United States, or any other country for that matter, to ignore a profitable source of energy? Consider a nation that intentionally neglects an energy source while their rivals pursue all possibilities. Is such a course wise, or is it path to irrelevance? Few predict a world with enough resources, energy, and prosperity to dispense with national rivalries before the need for this energy transformation. These factors detract from any future predictions. Although the EIA's reference case may prove accurate, any number of breakthroughs or world events would send their experts back to the drawing board. For these reasons, the security concerns for both solar and nuclear futures remain relevant as the world takes these steps toward a new energy future.

Considering both potential futures, the above security criteria can provide a few general recommendations. First, academic research must continue to refine the study of energy metrics such as EROI, outside the influence of market advocacy. The EROI data available today is insufficient to provide policy analysis beyond the broad-brush studies such as this one. With respect to the nuclear energy choice, nuclear advances must proceed in lockstep with non-proliferation dictates. Research and development to mitigate proliferation should precede the standard FBR plant designs to be implemented throughout the country. Both solar and nuclear futures provide an opportunity to advance resilience and security with updated designs and new construction. The U.S. government should play a part in this remake of the industry to ensure the security benefits come to

fruition. Collaboratively managing the design effort with private industry for standardized solutions may provide the required opportunity, even if such an effort requires federal funding. Massive adjustments to the power grid should provide sufficient redundancies to raise the cost to those who would seek to interrupt power. This would require several geographically separated links to the CSP plant capacity in the desert or to the larger wind farms. Direct federal investment or a revised market incentive structure to encourage investment in the U.S. power grid are required to update the aging power grid, addressing a primary infrastructure vulnerability for all energy futures. Solar markets should avoid dependence on any single rare-earth material, especially those controlled by other countries. Finally, a case must be made to garner support for the multi-trillion dollar investment required to achieve these shifts. This would likely require a world-wide campaign to publicize the benefits, consequences of failure, and the costs for such a transformation. New energy must become the new norm. Without this movement, local political, regional rivalries, and economics will trump any attempts for cooperative solutions which may require short term sacrifice. The United States has a leading part to play in this campaign as an advocate, an innovator, a provider, a partner, and a leader.

## APPENDIX – WORLD NUCLEAR REACTORS

World Nuclear Plants in Operation <sup>183</sup>		
Reactor Type	Average Capacity MWe	Number of Reactors
ABWR	1,287	5
AGR	599	14
BWR	871	88
FBR	397	2
GCR (Magnox)	354	4
LWGR/EGP	12	4
LWGR/RBMK	947	12
PHWR	333	23
PHWR/CANDU	693	21
PWR	952	217
PWR/VVER	721	47
<b>Grand Total</b>	<b>842</b>	<b>437</b>

### Reactor Abbreviations

APR	Advanced Pressurized Water Reactor
ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas-cooled Reactor
BWR	Boiling Water Reactor
FBR	Fast Breeder Reactor
GCR	Gas-cooled Reactor
GCR (AGR)	Old AGR
GCR (Magnox)	Magnox GCR
HTGR	High Temperature Gas-cooled Reactor
HWGCR	Heavy Water Gas-cooled reactor
HWLWR	Heavy-water-moderated Light Water-cooled Reactor
HWLWR/CANDU	Canadian Deuterium Uranium HWLWR
HWR	Heavy Water Reactor
LMFBR	Liquid Metal Fast Breeder Reactor

<sup>183</sup> World Nuclear Association, *Reactor Database*.

LWCHWR	Light Water-cooled Heavy Water Reactor
LWGR	Graphite Moderated Light Water Cooled Reactor
LWGR/EGP	EGP - LWGR
LWGR/RBMK	RBMK - LWGR
LWR	Light Water Reactor
Na-graphite	Na-graphite
OMR	Organic Moderated Reactor
PHWR	Pressurized Heavy Water Reactor
PWR/VVER	Russian PWR
VVER	Russian PWR

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